PETROLOGY AND SEDIMENTATION OF THE MILLSTONE GRIT OF SCOTLAND

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INTRODUCTION

The present study of the Scottish Millstone Grit has been undertaken with the object of elucidating the problems of source, transport, and depositional environment of the sediments of that age.

The nature of the source rocks is deduced from the mineralogy of the sandstones; their distribution from a consideration of thickness and facies variation, directed sedimentary structures, grain orientation, median grain size and areal mineral variation. The character of the transporting medium and the distance of transport are reflected in the roundness, grain size, and mineral content of the sandstones. The depositional environment is resolved, in broad outline, from the lithological association, and in detail by comparison of the grain-size distributions with those found in different present-day environments, together with a consideration of facies variation, sedimentary structures, grain-orientation and the development of authigenic minerals.

The lateral and vertical variation of these characters is used to determine in how far the Scottish Millstone Grit can be regarded as a unit distinct from the Upper Limestone Group and Coal Measures. Finally an attempt is made to collate all the various facts and present as complete a picture of the Namurian physiography of the Midland Valley and its environs as is possible.

b) Description of Area.

Scottish Millstone Grit strata outcrop in three discrete areas of the Midland Valley. The largest of these forms the discontinuous girdle surrounding the Coal Measures of the Central Basin: further east is the uninterrupted outcrop around the Midlothian Coalfield and its northern extension across the Firth of Forth: less regularly distributed representatives of the series also occur in Ayrshire. The total area of outcrop is 136 square miles; 98 in the Central Basin, 24 in Midlothian, and 14 in Ayrshire. The extent and relative positions of these areas is indicated in fig. 1. The present study has dealt almost exclusively with the Central and Midlothian basins.

c) Structure.

In both of these areas the beds form part of a basin with a north-south elongation. The major folding is about a north-south axis but the Central Basin is also traversed by a series of very gentle east-west folds. Both basins are assymmetrical, the east side of the Central Basin and the west side of the Midlothian Basin dip at 20° and 40° respectively while the opposite limbs have a mean inclination of only about 10°. Numerous faults with an east-west trend have produced major dislocations in both basins. The only obvious unconformity occurs around the southern margin of the Central Coalfield where the whole of the lower part of the Millstone Grit together with the upper beds of the Upper Limestone Group are missing

d) <u>Age</u>.

The Scottish Millstone Grit, as arbitrarily defined, includes those strata between the Castlecary or No. 6 Limestone and the Crofthead Slatyband Ironstone and its lateral equivalents. Whether these limits actually delineate a cognate series of beds which differ significantly from the underlying and overlying groups will be discussed later.

Bisat's classification (1924) extended the Millstone Grit of the North of England to include goniatite zones E_1, E_2, H, R_1, R_2, and part of G. Goniatites are almost unknown in the Scottish Millstone Grit but it has been shown (Currie, 1954, p. 537) that the E zone is the equivalent of the Limestone Coal Group, the Upper Limestone Group, and possibly the base of the Millstone Grit where the few goniatites might be from the top of zone E or the lower part of zone H. The next goniatites identified are from Skipsey's Marine Band at the top of the Coal Measures and these belong to Bisat's Zone A. Currie considers (p. 538) that zone A includes the greater part of the Coal Measures strata, and hence the bulk of the Millstone Grit together with the lower part of the Coal Measures must occupy some part or all zones H, R, and G. Dinham and Haldane (1932, p. 114) consider that zones H and R are missing in Scotland and present as 'good grounds' for this belief the fact that in Lancashire these beds have a maximum thickness of 1800 ft. Since there may be as much as 1500 ft. of lithologically similar goniatite-free beds in the Scottish Millstone Grit, thickness alone is no criterion for posulating a break.

Macgregor and Pringle (1934, p. 6) also consider zones H and R to be absent but can present no evidence of this from the Central and Midlothian basins. In fact to support the theory they recognise that the 'plant break' would have to be ascribed to the E zone and not as in England to H, despite the fact that the only goniatites present at the base of the series, some 250 feet lower, may well belong to the H zone. Currie (1954) admits that "evidence of the occurrence of a 'goniatite break' is only negative since goniatites have not so far been found higher in the Millstone Grit than 30 feet above the Castlecary Limestone."

The disappearance of the 'Nebraskan' fauna and Kidston's well known plant break close above No. 3 Marine Band have also been cited in support of a great 'hidden' unconformity. Now the lithological and mineralogical attributes of the sandstones indicate that at this horizon there is a change in the depositional environment from shallow marine to deltaic, slight uplift to the south of the Central Basin and on the west side of the Midlothian Basin, but no change in mineralogy such as might be expected to result from erosion of the source during a long period of non-deposition. Furthermore, above the 'unconformity' there is no development of conglomerates, gravels or even coarse sandstones except in the south of the Central Basin. If, as these facts suggest, there is no unconformity how can the faunal and floral changes be accounted for? Since there is a change from shallow marine to deltaic conditions it is to be expected that there will be a decrease in salinity and a change in other factors so that 'Nebraskan' lamellibranchs, adapted to Lower Millstone Grit conditions would no longer be expected to persist. The 'plant break' is little more rapid than that found in the North of England where it is not considered to indicate any gap in the succession. It may possibly represent the sudden incursion into the area of a more rapidly evolving flora from further south, and a few lower Carboniferous species do persist. Moreover the small vertical gap between Lower and Upper Carboniferous forms is best demonstrated in the Midlothian Basin very close to the one place where very thick development of coals indicates a long period when little detritus was being deposited. The Scottish Millstone Grit, divested of its singularly well hidden 'unconformity', becomes a series of shallow water deposits being more or less continuously deposited over the same period that a lithologically similar series was being deposited in the North of England, the Yorkshire Millstone Grit which, as described by Gilligan, occupies zones H, R and G.

e) Lithology.

Within the lower third of the series parallel-bedded flaggy sandstones are interspersed with about an equal thickness of shales and fireclay. Close above the Castlecary Limestone coarse grit bands are common but upwards in this lower part of the Millstone Grit there is a gradual diminution in grain size so that the top 100 feet are of siltstone and shale. Ironstones are common at this horizon on the west side of the Midlothian Basin and a 14 foot seam of coal has been recorded in a recent boring at Musselburgh. Thereafter there is a marked change of lithology and massive white, grey, red and brown current-bedded sandstones predominate with but a few thin bands of shale. Coarse grit bands are common, particularly towards the top of the series. At 4 horizons within the lower part of the Millstone Grit there are thin bands of limestone or limy shale which carry marine fossils. Of the 4, designated Nos. 0, 1, 2 and 3 Marine Bands only No. 2 is almost invariably present. The further 2 Marine Band Groups, Nos. 5 and 6, occurring in the upper part of the series are associated with shales and not with limestones. Thin coals and ironstones, rarely more than a few inches thick are present at several horizons.

f) Previous Mineralogical Research.

While the lithology of the Scottish Millstone Grit has been described in various Geological Survey Memoirs, the only previous work of a petrological nature was the examination of only 6 vertically and areally distributed concentrates by Bosworth (1913). In the North of England the first study by Sorby in 1859 was concerned mainly with the lithology of the series in South Yorkshire though there is also a description of the commoner minerals and rock fragments. Hull (1864) and Green (1868) discuss the lithology and thickness variation of the Millstone Grit of the North of England and show a marked southerly attenuation of the sandstones. A more detailed study of the mineralogy of the Yorkshire Millstone Grit by Gilligan (1919) was accompanied by a discussion on the general nature and location of the source area which was considered to lie in Scandinavia and the Scottish Highlands. The beds are supposed to represent the deltaic deposits of a river of Mississippian proportions.

PETROGRAPHY OF THE ARENACEOUS DEPOSITS

The Millstone Grit Series consists almost entirely of sandstones, clays, and shales but in a few areas, notably in Clackmannan and Midlothian, there are coarser grit bands containing pebbles which may attain a length of 1½ cms.

a) **Pebbles.**

The material of pebble-size consists in very large part of quartz, which is commonly milky-white, clear, or opalescent, and more rarely pink or yellow. The pebbles always exhibit a greater degree of rounding than the particles of sand size with which they are associated. Their mean roundness is about .45. Microscopic examination reveals that the extinction of all the quartz pebbles is very undulose and hence they must have been subject to mechanical deformation which has frequently been so intense as to produce beautiful mylonitic structure (Plate 2). Mortar structure is less common. Many of the pebbles are composed of several interlocking grains of quartz within which anhedral blebs of microcline are rarely included. Trains of opaque dust and liquid globules are the most common type of inclusion. Regular crystals of zircon, rutile, tourmaline, apatite, biotite, magnetite, and possibly sillimanite, are also numerous.

The few pebbles of feldspar are readily identifiable by their white surface alteration. They are nowhere more than 5 mm. in length. The only variety present is a remarkably fresh microperthite whose properties will be described when dealing with the feldspar of the finer material.

b) Sandstones.

The sandstones are for the most part orthoquartzites. Quartz, feldspar, micas, and occasional small rock fragments together with a variable amount of clay matrix constitute 99.9% of the detrital constituents of these sediments.

i) Light Minerals.

Quartz.

Angular to sub-rounded grains which frequently display appreciable secondary growth with consequent development of prism edges. The degree of secondary development is inversely related to the amount of clay matrix and is completely inhibited where there is sufficient matrix to form a veneer on the surface of the grains. Even where secondary deposition is appreciable growth is arrested at any point, where a small clot of clay material infringes on the growing boundary. In those sandstones with more than 10% of intersitial clay slight corrosion of the quartz grains is apparent. More marked corrosion is observed where a haematite cement is present, and is here accompanied by shattering of the grains and subsequent infilling of the shatter cracks by haematite.

The percentage of grains showing signs of having been subjected to pressure varies between 32 and 91: there is a slight correlation between median grain size and percentage of strained quartz (cf. Gilligan 1919, p. 260) as shown in fig. 2. Mylonitic structure is common in the larger grains, in rare cases forming a zone traversing an otherwise unstrained crystal. There are numerous polygranular fragments whose component parts are sutured together. Strain has occasionally produced an effect of simple or repeated twinning (Plate 3). Dauphine twinning is very common.

None of the quartz grains is entirely free from inclusions: most contain trains of liquid globules and opaque dust which may either be sub-parallel or may cross one another at a high angle: many more have regular inclusions (zircon, tourmaline, rutile, apatite, quartz, muscovite, biotite, and hornblende), which are rather more common than irregular inclusions of magnetite and acicular needles of rutile and sillimanite. The extremely faint reticulate pattern observed in a few grains is probably also due to minute inclusions and is possibly an exsolution effect.

A curiousity of the strained quartz is the very occasional development within it of concentric zonary structure, each zone having the shape of a euhedral quartz crystal with pyramidal terminations.

Feldspar.

Three types of feldspar - sodic plagioclase, microcline, and perthitic orthoclase - are present in about equal quantities and together commonly constitute about 1% of the detrital material. The plagioclase and orthoclase have undergone a variable but generally slight amount of kaolinisation but the microcline is extremely fresh. When anhedral the grains are better rounded than those of quartz. They are also more subject to corrosion and fracture.

Sodic Plagioclase.

This occurs as short stumpy prisms with ragged terminations. Composition is rather variable. The most common variety is Albite-Oligoclase An_5-An_{20} a little sodic andesine An_{20}-An_{35} is however sometimes present in the Clackmannan sandstones. The twin lamellae may be curved. There are only a few inclusions of iron ore.

Potash feldspar.

This group is rather more abundant than plagioclase. Microcline, with its characteristic but very variable quadrille structure, occurs as glassy clear, angular, equant grains in which blebs of quartz, zircon, and iron ores are commonly included.

In many crystals exsolution of albite has produced perthitic structure which is frequently not uniformly developed throughout the grain. The individual lamellae tend to be lenticular, interfingering, and are often curved, contorted, or even fractured and displaced (Plate 3).

There remain the homogeneous forms which occur as laths or as rhombohedra the latter form being controlled by a perfect (001) and a distinct (110) cleavage. The simplest forms are untwinned or twinned on the Carlsbad law but incipient development of microcline twinning in part of the crystal may rarely be observed. Inclusions are very common, consisting of blebs of quartz and iron ores together with mica and zircon which are frequently aligned parallel to the twinning. From the optics of the apparently homogeneous crystals it would appear that either the composition or the molecular arrangement or both must vary widely. This is best revealed by the wide scatter and binodal distribution of the values of the optic angle of 12 crystals measured on a universal stage. Four have angles in the 60-72° range, 7 between 80° and 87°, while one is optically positive with $2V = 88^{\circ}$. In other crystals where an optic axis figure was obtained, the isogyre was almost always so straight as to indicate an optic angle in excess of 80°. The lower group are monoclinic and apparently normal members of the orthoclase family. In the others however the orientation is such that Y makes an angle of 15° with C, as computed from the cleavage, while X does not coincide with A. This is therefore a triclinic feldspar whose optics are closely akin to those of microcline save that the X and Z axes occupy a slightly different position. A astereogram of the mean form of this feldspar is shown in fig. (3).

Mica

Almost all of the sandstones contain a few shreds of muscovite which may be as much as 4 mm. long. There may also be considerable authigenic development of biotite. Such development is dependent upon the presence of Fe^{++} ions and culminates in the very ferruginous sandstones in a matrix composed entirely of large biotite flakes and limonitic aggregates (Plate 8). In the iron-free sandstones sheets of biotite frequently occur along certain of the bedding planes where the necessary iron could be derived from ground waters to combine with the clay marking the bedding plane. Small laths of white mica may abound wherever there is a clay matrix.

ii) Rock Fragments.

Small fragments of chert are fairly common in amounts of less than 1%. Organic structures have never been observed. Fragments of metamorphic rocks other than quartzites are extremely uncommon; only two small pieces of low grade schist and two of a fine-grained schistose grit were present in all of the slides examined.

iii) Matrix and Cement.

Two types of cementing material are present; the one, of detrital origin, is a fine-grained clay with quartz fragments: the other, a chemical precipitate of calcite, dolomite, haematite, limonite, and, less commonly, silica. Where very little of either of these types is present, lithification has been affected by a slight suturing together of adjacent grains (Pl. 4). A study of borehole specimens has revealed that the amount of suturing increases with depth and with decreasing grain size and it is therefore considered to be controlled by the pressure of the overburden and by the number of contiguous grain boundaries. The secondary silica is in optical continuity with the grain on which it is being deposited but may frequently be distinguished by its lack of inclusions and by the impurities trapped around the original detrital grain. There is a marked tendency towards the formation of crystal faces particularly where there is sufficient pore space to allow of unrestricted development. Suturing takes place not only between grains of the same mineral but also between quartz and feldspar (Plate 5) when the differential growth or recession of individual feldspar twin lamellae produces a steplike contact. Where cohesion is dependent on suturing the sandstone is invariably very friable.

Most of the sandstones contain 5% or more of intersitial argillaceous material in which diagenetic changes have produced sericite fibres, chlorite, calcite, and, where iron is present, biotite.

Where the amount of a chemical cement is insufficient to completely fill the pore space of a sandstone it segregates into spherical patches enclosing a few grains or else occupies the bedding planes. In those sandstones with a carbonate cement there is optimum development of secondary crystal growth: in contrast an abundant haematite or limonite cement produces corrosion and fracture (Plate 6). Large euhedral crystals of yellow rutile can often be seen growing within the haemetite. Least common of all cementing materials is chalcedomy which is present in only a few of the coarser sandstones, usually in conjunction with calcite. The habit is commonly of little sheafs of radiating fibres but occasional complete spherulites are formed. In these the nucleus is almost always a small plant fragment. There is variable but generally imperfect development of radial structure and no concentric rings. Argillaceous and ferrous inclusions are abundant. (Plate 7)

iv) Description of Heavy Minerals.

Some 28 species of heavy minerals, detrital and authigenic, have been identified in the Millstone Grit sediments. These are:-

Cubic: Fluorite, Garnet, Magnetite, Pyrites, Sphalerite, Spinel

<u>Tetragonal</u>: Anatase, Rutile, Zircon

<u>Trigonal-Hexagonal</u>: Apatite, Corundum, Ilmenite, Tourmaline

<u>Orthorhombic</u>: Brookite, Celestite, Chloritoid, Hypersthene, Staurolite, Topaz

<u>Monoclinic</u>: Actinolite, Augite, Clinozoisite, Epidote, Glaucophane, Hornblende, Monazite, Pigeonite, Sphene.

Of these the 4 most abundant species are described first. The remaining species are dealt with in alphabetical order. The mean frequency value is computed only on those concentrates containing a given mineral and relates it to the total number of non-opaque minerals.

<u>Zircon</u>

Occurrence: 100%

Frequency: Mean 69% Range 0.7 - 84.9%

Average size: 120 x 50 μ

Forms Present: By far the most common type of euhedral grain consists of a combination of a (100) or (110) prism with a (111) bipyramid. Several other bipyramids including (101) and (331) may also be developed but the terminal (001) pinacoid has been observed only twice.

Usually only 5% or less of the grains are euhedral, the remainder being cylindrical or ovoid. The elongation of the grains varies from 1.1 to 6.9 with a mean of 2.5. The colourless variety is by far the most abundant but pink or purple grains are also invariably present and pale yellow grains are not uncommon. A dusky brown variety is also found which frequently displays more obvious zoning than the other varieties. This zoning may affect the whole crystal or may be confined to the central portion. Parallel growth of 2 individuals is occasionally observed and there are also several grains in which an optically similar green band runs the length of the axis of the crystal. The few inclusions which do occur consist chiefly of long slender needles or small spherical blebs of zircon. Small euhedral grains of iron ore, little clots and stringers of opaque material, and cavities, mostly gas filled, are also present. The inclusions are irregularly distributed except in the few cases where they are massed together in the centre of the crystal.

<u>Rutile</u>

Occurrence: 100%

Frequency: Mean 12.5 Range 2.6 - 52.6

Average size: 155 x 70 μ

Forms Present: A combination of a tetragonal prism with the corresponding bipyramid was the only type observed. Geniculate twins are common. Abrasion has produced rod-like and ovate grains with rounded terminations and subhedral grains where only the prism faces have been preserved. 4 distinct colour varieties are recognised. The clear-yellow, fox red, and deep red varieties are almost free from inclusions but there is also a much darker variety pleochroic in purple-brown and often containing abundant inclusions of iron ore. It is considered that this latter represents the dark brown rutile described by Mackie as occurring in the foliated granites of the Highlands. Very small, euhedral, obviously authigenic crystals of the fox-red variety are rarely present.

Tourmaline

Occurrence: 100%

Frequency : Mean 10.5% Range 0.4 - 46.0%

Average size: 170 x 155 μ

The grain morphology is controlled to a considerable degree by the prominent (0001) parting of the mineral so that hexagonal to rounded basal plates are very common. There are also numerous small euhedral tabular crystals with pyramidal terminations and angular fragments of larger crystals. The following types are recognised on the basis of colour and pleochroism.

A. Brown:-

1. E. Yellow, Pale-brown

   O. Brown, Green-brown

2. E. Brown

   O. Very dark brown

3. E. Brownish-red

   O. Indigo

B. Green:-

1. E. Pale green

   O. Olive green

2. E. Green

   O. Brown

C. Blue:-

1. E. Light blue

   O. Light blue

2. E. Pale lavender

   O. Dark blue

3. E. Blue-black

   O. Blue-black

D. Colourless:-

1. E. Colourless

   O. Very pale pink, Very pale green

Multicoloured grains occur rather infrequently. The component parts are usually not strongly pleochroic. A combination of brown and green is most common but a green and blue variety has been rarely observed. Inclusions are numerous and consist of cavities, magnetite, needles of rutile, quartz, and zircon. Type A 1 is often crowded with carbonaceous inclusions. The inclusions are frequently aligned parallel to the prism edge. Colourless authigenic overgrowths are uncommon.

Garnet

Occurrence: 35.6%

Frequency: Range 0 - 88.0%

Average Size: 220 x 185 μ

Garnet is the most variable of all the heavy minerals. It is entirely absent from more than half of the separations in the Central

Coalfield, is a very minor constituent in most of the others, but in a few cases is the most abundant of all the heavy detritals. In the Midlothian Basin it is almost always present but is only occasionally the major constituent. The grains are commonly completely anhedral, angular and very beautifully etched but a few dodecahedra of the coloured variety do occur. There are two colour types: the abundant colourless to delicate pink variety and the much less common red brown grains which are only found when garnet is a major detrital mineral. The colourless grains very infrequently exhibit anomalous interference colours. Such grains are uniaxial, or biaxial with a very small optic angle. The optic sign is negative. Inclusions are rarely numerous although few grains are entirely free of them. They comprise iron ores, including small cubes of pyrites, zircon needles, quartz and biotite. Garnets of the sieve type crowded with inclusions of iron ore and rutile occur in the north-eastern part of the Midlothian-Fife Basin.

<u>Amphiboles</u>

Occurrence: 3.0%

Mean Frequency: 0.7%

Average size: 180 x 130 μ

Fray-ended prisms and angular fragments of green amphibole are an occasional minor constituent of the Fife sands. Pleochroic scheme X = pale yellow Y = green Z = olive green. From the low extinction angle, $Z \wedge C = 12^{\circ}$ it would appear that the composition is similar to that of actinolite. The grains are often crowded with opaque inclusions. Brown hornblende has nowhere been positively identified.

Anatase

Occurrence: 70.0%

Mean Frequency: 2.8%

Average size: 155 x 155 μ

Almost all of the anatase present in the concentrates is authigenic. Tabular (001) flakes with or without pyramidal modifications are almost the only forms present. A very few bipyramids with pinacoidal terminations and very distinct (001) cleavage have also been observed. The (001) tablets frequently display simple 'geometrical patterning.' Pale lemon-yellow to pale grey-yellow is the common colour though a delicate blue tint is found in the west. Anatase is frequently observed as authigenic outgrowths on ilmenite and sphene.

Apatite

Occurrence: 8.3%

Mean Frequency: 3.8%

Average size: 320 x 195 μ

Apatite is present only in the more garnetiferous concentrates, where it takes the form of large prismatic grains with rounded terminations. The mineral is colourless to very pale pink, has a distinct (0001) cleavage and contains numerous inclusions which are often crowded towards the middle of the grain. Fluid inclusions are frequently aligned either parallel to or making a small angle with the prism edge.

Brookite

Occurrence: 21.0%

Mean Frequency: 0.8%

Average size: 175 x 100 (D) 55 x 30 (A) μ

Most of the brookite is authigenic with minute prismatic habit; the honey-coloured, basal plates display characteristic interference figure and colours. Detrital grains, in the form of prisms with ragged ends are rare; these are striated parallel to the prism edge.

Celestite

Occurrence: 2.7%

Mean Frequency: 7.4%

Average size: 170 x 95 μ

Celestite is present in small quantity in some of the Clackmannan concentrates. The habit is prismatic, subhedral.

Chloritoid

Occurrence: 2.0%

Mean Frequency: 0.6%

Average size: 210 x 155 μ

This species is found only in the garnetiferous concentrates. The grains are almost all (001) cleavage flakes whose angular outline is controlled by 2 prismatic cleavages at 60° to each other. Pleochroic scheme X = yellow green Y = dusky blue Z = light green: depth of colour varies markedly with the thickness of the flake. Inclusions of quartz, rutile, and iron ores are numerous.

Clinozoisite

Occurrence: 2.7%

Mean Frequency: 1.4%

Average size: 180 x 160 μ

Clinozoisite occurs but infrequently as colourless or pale grey, rounded, mammilated grains which almost invariably exhibit an optic axis interference figure which is biaxial positive with 2V = 85° ±.

Corundum

Occurrence: 1.7%

Mean Frequency: 0.5%

Average size: 135 x 120 μ

Colourless to very pale blue, angular basal flakes of corundum are found very sporadically on the west side of the Central Basin.

Epidote

Occurrence: 20.0%

Mean Frequency: 1.3%

Average size: 130 x 80 (green) μ 360 x 280 (colourless) μ

Small, colourless to pale green, angular fragments of epidote are present in small numbers in many of the concentrates. The grain surface may be coated with red-brown alteration products. There are only a few inclusions of iron ore. In the Glasgow district another variety is encountered. This occurs as large (.4 - .5 mm.) angular water clear grains; biaxial negative 2V = 85 - 89°.

Inclusions of iron ore and rutile are common.

Fluorite

Occurrence: 6.0%

Mean Frequency: 0.5%

Average size: 560 x 340 μ

Fluorite is a minor constituent of several of the garnetiferous sands. The grains are large, acutely angular, colourless, pink, or pale blue. Inclusions are rare but the presence of iron ores or fluid inclusions does occasionally result in the grain being weakly birefringent.

Glaucophane

Occurrence: 0.7%

Mean Frequency: 0.3%

Average size: 260 x 180 μ

Glaucophane is rarely present and is found only in Fife. The grains are pleochroic, the terminations ragged, and there is very strong pleochroism in blue and lavender. The extinction angle never exceeds 8^{o}.

Iron ores

Occurrence: 100%

Average size: 190 x 175 μ

Ilmenite, by far the most abundant of the iron ores, usually comprises about half of the total concentrate. The mineral occurs as discrete angular fragments and as small aggregates both of which may frequently be encrusted with small authigenic outgrowths of anatase: alteration to leucoxene is nowhere extensive. Detrital magnetite is much less plentiful. Rarely however there are numerous minute, authigenic, octahedra. Heavily striated grains of pyrites are present in small numbers in the extreme south-west of the Central Basin and in Midlothian. Haematite occurs only as a cementing material and as such is sometimes abundant.

Monazite

Occurrence: 50.3%

Mean Frequency: 1.4%

Average size: 105 x 75 μ

A common minor detrital constituent, this mineral invariably occurs in the form of small well rounded or ovate grains of a lemon-yellow or honey colour. A few exhibit a well developed (001) cleavage. There may be numerous inclusions of iron ore and the surface of the grain is usually encrusted with brownish decomposition products.

Pyroxene

Occurrence: 7.3%

Mean Frequency: 0.8%

Average size: 195 x 150 μ 210 x 175 - Pigeonite μ

Although pyroxenes are scarce 3 different species have been identified. All 3 occur as prismatic or angular grains. The brown variety, common augite, is nearly always badly altered. Fresh hypersthene showing striking pleochroism in pinkish-brown and green is present in a few Clackmannan concentrates. The least common variety occurs only to the south of Linlithgow on the eastern side of the

Central Basin. The grains are here remarkably fresh and free from any inclusions save a few particles of iron ore. Pleochroic scheme X - very pale brown Y = pale brown Z = pale brown-green. The optics of the mineral biaxial positive, 2V = $12^{\circ} \pm 2$, Z C = 36°) would seem to indicate that it is Pigeonite.

Sphalerite

Occurrence: 3.3%

Mean Frequency: 0.4%

Average size: 100 x 70 μ

Small brown (110) cleavage fragments are found sporadically throughout the area.

Spinel

Occurrence: 3.7%

Mean Frequency: 0.4%

Average size: 180 x 120 μ

The pale bluish-green variety Ceylonite is among the rarer of the detrital species. The grains are ovate and their surface is commonly slightly pitted. Two grains have been observed which were sheathed in green epidote. There are very few inclusions.

Sphene

Occurrence: 20.6%

Mean Frequency: 1.3%

Mean size: 160 x 115 μ

A neutral and a water clear variety rather similar to zircon are both present. They occur as angular fragments which may be distinguished by their failure to extinguish and by their interference figure (Bramall, 1928, p. 39).

<u>Staurolite</u>

Occurrence: 2.3%

Mean Frequency: 1.0%

Average size: 285 x 220 μ

Staurolite is never present in any concentrates from the main outcrops of the Central and Midlothian Basins but it can be positively identified in the garnetiferous sands of Glasgow and East Fife. Raggedly terminated prisms are found together with a perfectly euhedral platy form, controlled by the (010) cleavage and terminated by (101) dome faces. There are numerous, frequently euhedral, inclusions of quartz and iron ore. Pleochroic with X = colourless, pale brown Y = golden yellow Z = honey brown.

<u>Topaz</u>

Occurrence: 0.3%

Mean Frequency: 0.7%

Average size: 160 x 145 μ

Glassy clear anhedral grains of topaz were found in only one concentrate. In addition to these minerals there were a few grains which defied positive identification. None of these species was recognised in more than one concentrate. Flakes of biotite, chlorite, and serpentine were frequently present in the concentrates but were not considered with the heavy detritals.

LATERAL VARIATION IN THICKNESS OF THE MILLSTONE GRIT

It has long been recognised that the Millstone Grit of the Midland Valley of Scotland is subject to considerable variations in thickness when traced laterally. Accounts of local variation are recorded in several of the Memoirs of the Geological Survey. The Series has been considered to be thickest in the northern part of the Central Coalfield and to thin south-westwards towards Ayrshire.

Macgregor (1931) points out that 'The variations in thickness shown by the various subdivisions of the Scottish Carboniferous are due in the main to attenuation of the sediments and not to non-deposition or overlap.'

Richey (1935) indicated the existence of north-easterly trending faults, across which abrupt changes take place in the thickness of the Lower Carboniferous sediments of Ayrshire. He suggests that these variations are continued north-eastwards into the Central and Midlothian. From these variations he concluded that submarine faults were active throughout Lower Carboniferous times and produced steep scarps with increased sedimentation on the downthrow sides and decreased sedimentation on the upthrown sides.

That no attempt has been made to draw an isopach map of the Millstone Grit is due in part to the uncertainty of correlation of the base and top of the Series in the different basins. In the Central Basin the base is the Castlecary or Levenseat Limestone. This horizon can be recognised everywhere except along the southern and north western margins of the basin where it may not be present either as a result of non-deposition or erosion. The use of the Crofthead Slatyband Ironstone to mark the top is much less satisfactory since it is frequently absent. In those cases the top is taken to lie a little way below the lowest coal of the overlying Coal Measures. In Midlothian the base and top have been taken to be represented by the No. 6 Limestone and the foot coal. In Ayrshire the boundaries are the top limestone of the Upper Limestone Group and the Dalmellington and Lugar Blackband Ironstone. The choice of this latter horizon is questionable since it coincides with the appearance of <u>Carbonicola pseudorobusta</u> Trueman which does not occur in the Central Coalfield till almost 250 feet above the base of the Coal Measures. Nevertheless while the top part of the Millstone Grit of Ayrshire is probably coincident with the lower part of the Coal Measures elsewhere the Dalmellington Blackband Ironstone is used as the top of the Ayrshire Millstone Grit in the construction of the isopach map because of the absence of a suitable lower horizon. The values shown for the Ayrshire Basin may therefore be somewhat too high but the pattern of thickening and thinning of the Series is unlikely to be affected.

While this isopach map (fig. 4) may not quite show a variation in thickness between two horizons each of which is isochronous it does serve to outline the main trends of sedimentation and also indicates areas of greatest and least deposition. The isopachytes have been constructed largely on the basis of bore journals. In the absence of deviation surveys and because of the occasional uncertain identification of the base and top of the Millstone Grit, the figures recorded in these journals can only be regarded as approximate thicknesses. A few of the values have also been computed by the Geological Survey from natural sections.

The spacing of the 130 sites is not such as to afford a rigid control of the isopach contouring. Within each of the major basins control is reasonably good but elsewhere particularly in the case of the extrapolation of several of the zero margins, the contouring is largely conjectural and has been done mainly by assuming that the interval between the uncontrolled contours is more or less equal to the interval between controlled contours on the same margin of the basin. The 0 foot contour is not actually drawn. Instead all areas with less than 50 feet of sediments of Millstone Grit age are considered to be essentially areas of non-deposition. During the greater part of the Millstone Grit these areas rose above the level of water in the basins. It will be later shown that additional support for the presence and extent of these positive areas is afforded by a study of grain-size distribution, since towards these areas fluviatile or beach-type sands appear. That they made local contributions of detrital material is evidenced by the presence in the sands which fringe them of a heavy mineral suite different from that of the interior of the basins but similar to that of the Upper Limestone Group of the supposed positive areas (Chapter 6).

The most obvious and most important feature of the isopach map is the presence of distinct four areas of maximum thickness, one in each of the four present basins - Central, Midlothian-Fife, Douglas, and

South Ayrshire. It is therefore apparent that these four basins have not been produced, as has been supposed, by post-depositional folding and faulting with subsequent erosion. Had they been produced in this way there would be no reason for the areas of maximum thickness to be coincident with points on the axes of the present basins. Instead these basins are depositional features. Each was operative during deposition of the Millstone Grit, subsiding more rapidly than the stable areas between. When these basins were first formed is not at present apparent. Formation certainly precedes the deposition of the Upper Limestone Group for the isopach map of that formation produced by Goodlet (1956) shows similar, less well emphasised areas of maximum thickness in the Central, Midlothian and Ayrshire Basins, with thin deposits between.

At various times during deposition of the Carboniferous sediments, lavas were erupted in several areas of the Midland Valley. Extensive outpouring of Millstone Grit lavas occur in the area of non-deposition between the shallow North Ayrshire Basin and the larger South Ayrshire Basin. Local volcanic outbursts also took place around the margins of the East Fife Basin. It is significant that the lava plateaux of the Calciferous Sandstones and Carboniferous Limestone periods are also located between or around the margins of the various basins. It is considered that the position of these lavas were controlled by down-warping at the margins of the basins. At these points of buckling the crust is under tension and so the lavas can break through more readily there. If this is correct then some approximate margins of the basins can be drawn around the outcrop of the Lower Carboniferous lavas of the Renfrewshire Heights, Campsie Hills, Bathgate Hills, in the Central Basin and the Garleton Hills of East Lothian. If the location of these Lower Carboniferous lavas was controlled by the subsidence of the intervening basins then it follows that the basins must have been in existence at least from the beginning of the Carboniferous period. How much earlier they may have formed could only be determined by a study of the Old Red Sandstone sediments. It may be significant that the Lower Old Red Sandstone lavas of the Pentlands and Ochils are located just at the margins of one of the Carboniferous Basins but this could also be explained on the basis of the greater erosion which took place in these areas when they were comparatively stable and higher than the basins during the Carboniferous period. Fig. (5) shows the location and age of the various spreads of Lower Carboniferous lavas which fringe the basins and also the thickness of the Millstone Grit lavas. Thick Millstone Grit lavas occur only in Central Ayrshire on the upthrown block between the Dusk Water Fault to the North and the Inchgotrick Fault to the south. In this area the basalts may be over 200 feet thick. They thin rapidly to north and south. The lavas of the fringe of the Fife Basin are less than a third of this thickness. Laterally they are less persistent.

In the Central and Midlothian-Fife Basins the greater thickness of sediments is found towards the northern end of the basin suggesting that the main influx of material was from the north. In the Douglas-South Ayrshire Basin the thick deposits in the north-east indicate introduction of detritus from the north and east. Much of this material was derived via the Central and Midlothian Basins, introduced into the Douglas Basin, and spread south westwards into Ayrshire. The channel connecting the Central and Douglas Basins is quite apparent as a narrow area of greater thickness on the isopach map. The Midlothian-Douglas connection is much more tenuous because of the greater extent of older rocks which intervene.

In parts of the basin downwarping of the margins was sufficient to allow subsidence to continue: elsewhere there was a faulted junction between the stable areas and the basins. As the basin subsided movement took place along the fault. The effects of two such faults, the Dusk Water and Inchgotrick faults of Ayrshire have already been mentioned. Variation across the other Ayrshire fault, the Kerse Water Fault does not show clearly on the isopach map. To the north of it however, the sediments are about 100 feet thick: immediately to the south the thickness increases to 300 feet. Some movement was therefore taking place on this fault. The Southern Uplands Fault was also operative and marks the south eastern limit of the Ayr, Douglas, and Midlothian Basins. To the south of it little or no Millstone Grit strata are present. Movement on the Wilsontown Fault along the south-eastern margin of the Central Basin also seems to have taken place. This is the supposed north-easterly continuation of the Inchgotrick Fault of Ayrshire. Downthrow on that fault however, is to the south while on the Wilsontown fault it is to the north. If the faults are continuous the effect must have been of rotational or hinge faulting. From the spacing of the isopachytes the most apparent faulted junction is along the western margin of the Midlothian Basin. The crowding together of the isopachytes in this area - they should probably be even closer than can be shown - indicates movement along the Pentland Fault with the Pentland lavas rising above the western margin of the basin. Whether there was a continuous positive area between the Central and Midlothian Basins or whether another very shallow basin intervened between the Bathgate and Pentland lavas cannot be determined.

Sandstone and shale isolith maps were also drawn but since they showed essentially the same features as the isopach map they are not reproduced here.

An isopach map was also drawn of the strata between the Castlecary Limestone and No. 2 Marine Band of the Central Basin (fig. 6). Again the greatest thickness is found in the northern part of the basin indicating that from the very beginning of the Millstone Grit period the greatest influx had been from the north. The beds thin rapidly southwards towards the deeper central part of the basin. In the extreme south-eastern corner of the basin however, another marked increase takes place probably as a result of debris derived from the positive area to the south. At this time the barrier between the Central and Douglas Basins was not breached. The strata between the Castlecary Limestone and No. 2 Marine Band are here completely absent together with the top beds of the Upper Limestone Group, and the whole of the Millstone Grit is represented by a few coarse sandstones immediately underlying the base of the Coal Measures. Another less well marked area of more rapid sedimentation occurs in the north-west of the basin.

The sandstone and shale isoliths are again similar to the isopach. The limestone isolith however is rather different. For the purpose of construction of this isolith the Castlecary limestone has been considered together with the thin limestones of Nos. 0, 1 and 2 Marine Bands. Again there are three areas of maximum thickness (fig. 7), in the north, south-east, and north-west of the basin. The greatest of these, the northern, is quite remarkably bisected by a channel directed south-westwards in which very little limestone is found. Most affected is the Castlecary Limestone which is virtually absent from the channel yet over 10 feet thick a little way to north and south of it. One or more of the Marine Bands is also commonly absent from the channel. The variation in thickness in the Castlecary Limestone has been attributed by Francis (1956, fig. 4) to unconformity and erosion. Since the marine bands are also affected however, it is considered that this channel lies directly ahead of the mouth of one of the major rivers discharging into the basin. In this area the amount of detrital material being swept in was such that limestones were unable to form and so are replaced by thick calcareous sandstones. Even the greatly increased thickness of limestone on either side of the channel is partly due to the inclusion of clastic material.

LATERAL FACIES VARIATION

The lateral variation in the relative proportions of sandstone, shale, and limestone were investigated by means of ratio maps. Most informative of these proved to be the sandstone/shale ratio map (fig. 8). For the prupose of discussion of the map sandstone refers to a sand/shale ratio in excess of 4:1, shaly sandstone to ratios between 2:1 and 4:1, sandy shale to between 1:1 and 2:1 and shale to ratios less than 1:1. It is apparent that the sand/shale ratio will be highest where currents are strongest or where the recently deposited sediments are subject to considerable reworking with consequent removal of the fine material.

There is an almost continuous ring of sandstone around the Central Basin with the possible exception of the extreme western margin. This rim probably indicates the shallowing towards the margins of the basin. It is most extensive in the north where the greatest influx of material probably takes place. A very prominant tongue of sandy material projects into the basin just south of the eastern end of the Campsie Hills. This tongue coincides with a fairly rapid westwards attenuation of the sediments and with well-sorted sands in Stirlingshire. It is therefore considered to represent a relatively shallow area subject to strong current action. Within this ring of sandstone is a belt of shaly sandstone followed by sandy shale and finally by shale in the deeper southern part of the basin where the currents are very weak. The sandy shales are cut by a channel of shaly sandstone running southwards from Clackmannan. This channel coincides with the area of greatest thickness (fig. 4) and also with the low thicknesses of limestone (fig. 7).

The sediments of the Midlothian Basin tend to be finer than those of the Central Basin but again there is a coarsening from sandy shale to shaly sandstone towards the eastern and western margins of the basin and a southwards diminution of grain size with shale appearing in the south of Midlothian.

The most dominantly sandy sediments are found in the Douglas-South Ayrshire Basins which are filled with shaly sandstones with a rim of sandstone towards the Southern Upland Fault and an isolated patch of sandstone on the comparatively shallow area between the basins of Douglas and South Ayrshire. All of Central Ayrshire is covered by shale facies. This is almost an area of non-deposition and the high percentage of fine material largely results from the presence of the Ayrshire Bauxitic Clay, a weathering product of the lavas. The sediments coarsen once more in the shallow North Ayrshire Basin.

It was not possible to draw an accurate clastic ratio map because of the difficulty of deciding whether or not certain limestones belong to the Millstone Grit or to the top of the Upper Limestone Group. Thin limestones of undoubted Millstone Grit age are present only in the Central Basin and to a lesser extent in Fife. Elsewhere the limestones may be replaced by ironstones. This would tend to suggest that the waters of the Central Basin were more alkaline than those of the other basins. The question of the chemistry of the basins and more particularly of the sediments in them is discussed in a later chapter.

SEDIMENTARY STRUCTURES

a) Current-Bedding.

Current-bedding is a common feature of the Millstone Grit sandstones, but unfortunately is not equally well developed over the whole of the Central and Midlothian Basins. North of the Forth and in parts of Stirlingshire and Midlothian a great many of the sandstones exhibit well-marked current-bedding but elsewhere cross-stratification is either absent or so ill-defined as to prevent any accurate measurement of the foreset-slope direction. Such indistinct current-bedding is particularly common in the massive sandstones of the Upper part of the Series, and apparently results from a lack of markedly coarse or fine grained material along the bedding planes.

At least 3 types of unit can be recognised. Two of these accord very closely with the types described by Robson (1956, p. 256) from the Fell Sandstones of Northumberland. In the first of these the units are lenticular and 12 to 18 inches thick, the foreset beds are concave upwards and dip at about 30°. The other consists of a series of parallel units bounded by more or less horizontal bedding-planes. Each unit is 8 to 12 inches thick and again the foreset slopes are concave upwards. These two types correspond to Andersen's (1931) concave incline-bedding and continuous incline-bedding. In the massive coarse-grained sandstones there is a third type in which the units are 2 feet or more in thickness, and the foreset slopes are straight or slightly convex upwards. It is this type which is frequently so ill-defined. In all of these types topset beds are missing.

McKee (1957) points out that the absence of topset beds may result from a lowering of the water level and is therefore very common in delta-front strata.

While the current bedding generally lies undisturbed there are a few exposures where penecontemporaneous slumping has produced contortion and overfolding of the laminae. A particularly fine example from the Musselburgh area of the Midlothian Basin has been described by Clough (1910).

b) Ripple-Mark.

There is only a very limited development of ripple-marks in any of the Millstone Grit sandstones. Within the lower part of the Series asymmetrical ripples with a wavelength of 2" and an amplitude of ½" have been observed in the Cumbernauld District and shallow symmetrical ripples of slightly smaller amplitude occur in the top sandstones north of Carluke.

c) Mud Cracks.

Large polygonal mud-cracks have been observed in a few of the clays of Lower Millstone Grit age. Particularly fine examples occur in the Walton Burn south-east of Castlecary.

d) Direction of Prevailing Currents.

The direction of current movement in the two basins was established from the cross-stratification. Wherever possible the dip of the foreset-slopes was recorded on two intersecting rock surfaces and the true dip, after correcting for structural dip, was obtained by use of a stereogram. In those areas where current-bedding was very sparsely developed and where it could only be detected on a weathered surface the dip on only one surface was used provided that it exceeded 25°. Since the true dip of the foreset beds rarely exceeds 30° an apparent dip of 25° can only be recorded within 30° of the true dip direction. Nevertheless, because of its inaccuracy this method was very rarely used.

The current direction was also inferred from the few exposures of ripple-marks: the current trend was considered to be at right angles to the ripple crests, and its sense was given by the steeper slope of the ripple.

Fig. 10 is a stereogram of all the current-bedding and ripple mark normal directions recorded from below No. 3 Marine Band in the Central Basin. Three distinct groups can be recognised. In the major group the dip azimuth is between 215° and 300°; such units are often associated with other current-bedded units dipping towards 90 to 120°. Unrelated to these is a group dipping south-south-east to south while along the south eastern margin of the basin in the Levenseat area there are a few northerly-dipping foreset beds. The stereogram of the current bedding at different localities in the Upper Millstone Grit (fig. 11) is distinctly unimodal, the azimuth varying between 140° and 210°. This simplification in current pattern is accompanied by the establishment of much more uniform trends in the grain-size distribution (Chap. 6) and by areal restriction or disappearance of several minor sediment-petrographic provinces. It is therefore considered to be the result partly of the increased importance, the almost complete dominance, of the northerly sources; and partly to the configuration of the basin of deposition and to the location of the major outlets from that basin. The causes of current directions will be considered more fully later.

In the Midlothian-Fife Basin the current-bedding dips to the west or south-west along the eastern margin of the basin and to the south elsewhere. It would appear that as in the Central Basin the main influx is from the north with a second local source to the east and south-east of Midlothian.

e) Grain Orientation

i) It has been pointed out that cross-stratification is not developed throughout the whole of the area under consideration. A detailed study of the fabric of the sandstones was therefore undertaken in order to determine whether the grain orientation might be used to determine the direction of flow of the depositional medium.

Investigations of gravel fabrics were begun by Richter (1932) and modifications of technique were suggested by Wadell (1936), Krumbein (1939, 1940, 1942), and Schlee (1957). It is commonly found that pebbles tend to lie with their long axes parallel to the current but several factors influence the degree of preferred orientation. Cailleux (1945) noted that only the larger pebbles were oriented more by their contacts with other pebbles. White (1952) also found that degree of orientation decreased with decreasing size of pebble. Kahlterberg (1956) showed that the particle-size distribution determines the number of maxima of the long-axis direction of the pebbles. Where unequal sized materials are present there is only one maximum but where there is very little finer matrix, two maxima are found as a result of mutual interference. The scatter increases as the amount of matrix decreases.

The extension of orientation analysis to include fine-grained sediments was begun by Dapples and Rominger (1945), who were able to show that under experimental conditions sand grains tend to be oriented with their long axes parallel to the current. Furthermore 'tear-drop' grains are oriented with their broader ends pointing upcurrent. From a recent study Rusnak (1957) concluded that the fluid-flow direction can be deduced from an orientation analysis of the dimensional fabric of a sand deposit and that the more elongate grains tend to be more nearly parallel to that direction than the less elongate ones.

Few investigations of orientation in a natural environment have as yet been carried out. Curray (1956) has demonstrated the close relationship that exists between preferred orientation and backwash direction in recent coastal sands of the Gulf of Mexico.

The present orientation studies were performed on thin sections cut parallel to the bedding planes of the sandstone. A random part of the section containing about 400 grains was photographed and enlarged to simplify measurement of the least-projection elongation and end position (Dapples and Rominger, 1945, p. 251) of each obviously elongated grain. In addition, rod-shaped grains were considered alone to see whether they were better oriented. The elongation directions were arranged in 30° classes from 0° to 360° using end-position to indicate the sense of the elongation. In a few cases the grains were considered singly to reveal any features of the orientation pattern which are masked by grouping.

ii) Interpretation of Grain-Orientation Data.

There has recently been considerable discussion of the methods of analysis of orientation data. Early investigators treated their data as linear normal distributions for which they calculated mean and standard deviation. Jizba (1953) and Chayes (1954) indicate that the great shortcoming of this method is that it is necessary to choose an origin. A change of origin can produce a marked change in both mean and standard deviation of the distribution. Since in grain orientation analysis no a priori origin can be chosen the significance of linear descriptive parameters is very doubtful. Vector summation methods were devised (Reiche, 1938) to overcome this difficulty. Here each observation is considered as a vector, the north-south and east-west components of which are computed from the cosine and sine of the azimuth. These components are summed to give a resultant vector whose azimuth and magnitude are calculated in the following manner:-

$$\text{North-South Component} = \sum n \cos\theta$$

$$\text{East-West Component} = \sum n \sin\theta$$

$$\tan\bar{\theta} = \frac{\sum n \sin\theta}{\sum n \cos\theta}$$

$$r = \sqrt{(\Sigma n \sin \theta)^2 + (\Sigma n \cos\theta)^2}$$

$$L = \frac{100\, r}{n}$$

θ = azimuth from 0° to 360° of each observation

$\bar{\theta}$ = azimuth of resultant vector

n = number of observations in each class

r = magnitude of resultant vector

L = magnitude of resultant vector in %

Where no distinction is made between the ends of a grain the distribution covers only 180° so that each grain must be plotted twice, once in the 0-180° range and again in the 180-360° range. The resultant vector of such a distribution is invariable where the grains are considered singly but the magnitude of the vector will be zero. If the vector be calculated on a 180° distribution the azimuth will be without significance since the distribution in the eastern hemisphere will be without westerly components while north components will tend to balance south components. Thus the resultant vector will have a marked easterly component even where the true preferred orientation is almost north-south. Moreover the magnitude of the vector suffers from the same defect as the standard deviation of the linear normal distribution; it varies considerably if a different 180° arc is considered.

Krumbein (1939) attempts to remedy these failings and preserves the periodicity of distribution by doubling the observed vector angle and calculating as follows:-

$$\text{North-South Component} = \sum n \cos 2\theta$$

$$\text{East-West Component} = \sum n \sin 2\theta$$

$$\tan 2\bar{\theta} = \frac{\sum n \sin 2\theta}{\sum n \cos 2\theta}$$

$$r = \sqrt{(\sum n \sin 2\theta)^2 + (\sum n \cos 2\theta)^2}$$

$$L = \frac{100\, r}{n}$$

$$\bar{\theta} = \tfrac{1}{2} \arctan \frac{\sum n \sin 2\theta}{\sum n \cos 2\theta}$$

A disadvantage of this method is that it gives two possible directions of the azimuth which are 90° apart. Where orientation is pronounced then it is simple to decide which is correct but if the orientation is poor then it may be very difficult to decide by inspection. The magnitude of the resultant vector is also very different from that of the same distribution where the sense of each vector is known e.g. in an actual example the vector magnitudes were 22.2% for the original 360° distribution and only 14.3% using Krumbein's method.

All of these methods give only the trend and not the sense of the current movement and in order to overcome their shortcomings the end position of the grain was taken into consideration. This provides without manipulation a 360° distribution from which the azimuth and magnitude of the resultant may be directly computed.

This resultant azimuth is probably the best measure of central tendency of a normal circular distribution such as is likely to be found where the preferred orientation is controlled by one factor e.g. a current flowing in a given direction with a given velocity, but loses much of its significance as the distribution departs from normal to become bimodal or skewed. There are several factors which might produce such a departure: large grains rolling along the bottom may be differently orientated from smaller grains moving by saltation; strong cross-currents would tend to produce polymodal distributions; bottom slope might result in skewness. If any or all of these factors is important then the measure of central tendency of the whole distribution could produce misleading results. The use of the resultant magnitude is theoretically very questionable. For example in any count the magnitude will be zero if the same number of observations occur in each class interval i.e. no preferred orientation, or if they occur only in each of two diametrically opposed classes with no observations in any other class i.e. if all the grains are aligned in one direction. Now these two patterns would obviously be produced by very different currents yet no difference can be observed in the parameter which, to be useful, should give some indication of current strength and turbulence. Nor is it satisfactory to compute the resultant magnitude from a random 180° arc since as has been pointed out the magnitude varies with the chosen range. It would be necessary in each case to choose an arc symmetrical about the resultant azimuth. Such a cumbersome procedure would be justified only if there were some direct relationship resultant magnitude and current strength so that the latter could be computed from the former. Consider the deposition of grains on a smooth horizontal bottom. Where the bottom currents are very weak the grains, being subjected to only a very weak unidirectional force will be but poorly oriented. As the current strength increases the torque imposed on all non-equant grains will increase and so the degree of preferred orientation and resultant magnitude will become greater. So long as the bottom remains hydrodynamically smooth that is so long as there is a layer of laminar flow on the bottom then the preferred orientation will increase with increasing velocity. With continued increase in current velocity however the bottom becomes hydrodynamically rough and grains on the bottom are subject to turbulence and cross-currents which will tend to produce a more widely spread distribution and thus a lower resultant magnitude. It is therefore unlikely that this measure, calculated in this way, can be of any great value in determining current conditions. What possible alternative parameter might be used in place of the resultant magnitude? In its most hydrodynamically-stable position a grain lies with its broader end upstream and as the current velocity increases the tendency for the grain to assume this position will also increase. Even when laminar flow is replaced by turbulent flow the direction of the cross currents will be within 90° of the true current so that the grains will still lie with their pointed ends within 90° of the true current direction. The measure of velocity used in this study may be termed the 'end effect', E, which is given by

$$E = \frac{100\,(f_m - f_{m_1})}{n}\ \% \qquad \text{where}$$

f_m = Number of grains in a 180° arc about current direction

f_{m_1} = Number of grains in opposite 180° arc

n = Observed number of grains

In general the current velocity is related to the median grain size of a sediment and so the usefulness of E was tested by plotting it against median grain size, Md, as shown in fig. 12. It can be seen that where Md is below 130μ E is almost zero and may even be negative. Thereafter it increases rapidly with increasing median diameter till Md reaches about 210μ. At about this point where, as Inman (1949, p. 56) has shown, the threshold velocity of sand grains exceeds the roughness velocity i.e. where the bottom is hydrodynamically rough before movement is initiated the rate of increase of E with Md becomes less, probably because of turbulence effects. The approximate relations of E and Md in the areas of smooth flow (1) and turbulent flow (2) are

$$(1) \quad E = .22\ (Md - 130)$$

$$(2) \quad E = 13.5 + .03\ (Md - 210)$$

These relations are strictly applicable only to the present area since they will depend on the mean shape of the quartz grains composing a sand.

This measure, like the resultant vector, varies appreciably over short distances but it does at least go on increasing with increasing current velocity and is very rapidly calculated.

A measure of central tendency based only on part of the distribution might also be used. Most obvious is the mode but this can vary by at least a half of one class interval. The 'primary modal group' of the distribution may be defined as that class or group of adjacent classes in which the observed number of readings, f_o, exceeds the expected number f_e by the greatest amount. The values $(f_o - f_e)$ for each class interval in the group are then treated as a linear normal distribution whose mean can be calculated. In order to minimise the effect of departure from the current direction, or the least projection elongation of the grains under the influence of some factor other than the current e.g. bottom slope, the 'antimodal' group i.e. those class intervals 180^o removed from the primary modal group, was also considered. To the excess number of grains in each class interval of the primary modal group was added the excess for the diametrically opposed class. Negative values were not considered. The validity of treating the data as a linear normal distribution should also be considered.

If a grain is lying with its long axis inclined at an angle α to the current direction then the rotational force on the grain pivoting about one point varies with $\sin\alpha$. The current direction could therefore be derived by equating the rotational force on those grains on either side of the current direction. If 2 class intervals are involved then:

$$P \sin \alpha = Q \sin (i - \alpha) \quad - \quad (1)$$

$$\bar{\theta} = Pa + \alpha$$

where

P = $(f_o - f_c)$ for 1st class interval

Q = $(f_o - f_e)$ for 2nd class interval

Pa = azimuth of 1st class interval

i = angular extent of class interval

α = angle between Pa and mean direction

$\bar{\theta}$ = mean direction

If 3 classes are involved then

$$P \sin (i-\alpha) + Q \sin \alpha + R \sin (i + \alpha) = 0 \quad - \quad (2)$$

$$\bar{\theta} = Qa - \alpha$$

For 30° class intervals these resolve into

$$(1) \quad \tan \alpha = \frac{Q}{2P + \sqrt{3}Q}$$

$$(2) \quad \tan \alpha = \frac{P-R}{2Q + \sqrt{3}(P+R)}$$

The values of $\bar{\theta}$ got by using (1) or (2) are found to be the same as those obtained by treating the modal group as a linear normal distribution since such a distribution is also a function of the sine of the angular departure from the mean.

Four measures of central tendency were therefore considered mode, resultant vector of the whole distribution, mean direction of the excess grains in the primary modal group, and mean direction of excess grains in the primary modal + antimodal group. The most useful of these 4 will be that one which varies least with change of origin and which is most closely related to current direction. The effect of shift of origin and relation to current bedding direction is illustrated in

Table (1). With a 15° shift of origin i.e. the shift likely to produce the greatest change in the apparent current direction the mean shift is 13° for the mode, $12\frac{1}{2}^{\circ}$ for the resultant vector, 5° for the primary modal group and $4\frac{1}{2}^{\circ}$ for the summed modal and antimodal groups, i.e. the last value is the one least affected and hence the best measure. This same measure is most closely related to the current bedding and hence has been used throughout this study as the measure of current direction. The variation in the azimuth of the resultant vector with shift of origin and its occasional marked departure from the current-bedding direction is due to the sensitivity of angular functions to skewness of the distribution.

iii) Orientation Pattern of Grouped Data.

There is a marked variation in the form of the orientation diagram with changing grain size of the sediment. Silts and very fine sands display only a very weak preferred orientation (fig. 13a): the distribution is polymodal and the primary mode has never more than a 20% excess in the number of grains over the expected number. As the median diameter increases above .125 mm. the orientation improves very rapidly and the distribution has 2 very distinct modes 180° apart. Almost the same number of grains, 60-95% in excess of the expected number, occur in each mode (fig. 13b). This pattern is retained with a gradual slight increase in the size of one mode with respect to the other till the median grain size exceeds .150 mm. Thereafter, while the slightly increasing difference between the primary modes is maintained, 2 secondary modes are commonly present at right angles to the primary modes (fig. 13c). Normally there is only about a 10-20% excess in these modes but occasionally they are so strongly developed as to contain almost as many grains as the primary modes. Here it would be very difficult to decide the current direction were it not that the secondary modes are almost equally developed while by now one of the primary modes is much larger than the other. The excess percentage in the larger of the primary modes falls to 40 to 50 because of these secondary modes. As the median diameter passes through .2 mm. the smaller of the primary modes has only a few excess grains and by .25 mm. it has disappeared and the secondary modes are absent or not strongly developed. In the coarse sands $\frac{3}{4}$ of the grain elongation vectors lie in a 150° arc about the current direction and within this arc there are commonly at least two modes which may be as much as 60° apart (fig. 13d).

It seems likely that the silts and very fine sands are being deposited largely from suspension onto a bottom where there is very little flow and hence little preferred orientation. On the bottom on which the fine sands are being deposited there is a layer of laminar flow of sufficient velocity to orient a large number of grains. The secondary maxima may be due to grains rolling along the bottom with their long axes normal to the current and coming to rest in that position. As the current strength increases the 'end position' effect becomes more pronounced so that one of the primary modes is enlarged at the expense of the other. The strong development of turbulent flow and cross currents produces the spread and bimodal character of the distribution in the coarse sands.

Where only rod-shaped grains are considered the same sequence of changes in the orientation pattern are observed. Occasionally however, such grains are fairly well oriented when the pattern for all grains is almost isotropic. In general the modes of the orientation of rod-shaped grains are more sharply defined than the corresponding modes for all shapes of grain.

iv) <u>Skewness of Orientation</u>.

In several of the orientation diagrams the two primary modes are separated by 150° instead of 180°. It is difficult to see how such offset could be produced by cross currents and it is therefore considered to be produced by a slight slope of the bottom at right angles to the current direction and to have occurred either at the time of deposition or else less probably during compaction when slight downslope movement would take place. The quartz grains being measured have a slightly greater diameter at one end than at the other and so may be considered ideally as truncated cones. If a grain of this shape is on a bottom sloping at right angles to the current direction its resulting orientation will be controlled by 3 forces; the force imposed by the current which will tend to align the grain parallel to the current; the force of gravity which will induce the grain to roll downslope; friction which will resist any sort of movement. If the gravity force is greater than the frictional drag the grain will start to roll and as it does so the broader end will move further so that the grain, no longer aligned parallel to the current, will be subject to a force acting against the rotation produced by rolling. These forces will balance and the grain will be in an equilibrium position when the broader end is slightly downslope, so that the maxima of grains pointing upcurrent and downcurrent will be offset, the smaller angle between the maxima indicating the upslope direction. Slight downslope movement may also take place during compaction but because of the greater interference from adjacent grains it would be more difficult to produce offset.

That this skewness may be related to the general configuration of the bottom of the basin is suggested by the areal distribution of obviously skewed patterns. Of the skewed distributions with north-south primary modes in the Upper Millstone Grit 3 of 4 on the eastern side of the Central Basin are skewed to the west while all on the west side are skewed to the east.

The secondary maxima $\perp^{r}$ to the current direction are also frequently unequally developed. This again may well be related to the stability of a grain on a slope. Dapples and Rominger (1945, p. 260) showed that on a slope most grains tend to have their pointed ends downhill. On the east side of the basin 5 of 6 have the greater secondary maximum to the east while all 4 on the west have a larger westerly maximum.

From both skewness of the primary modes and inequality of the secondary modes it would appear that the bottom of the 'basin' dipped outwards at any time during deposition of the sands and not inwards as might be expected. On the south side of the basin the secondary mode at 180° is usually more strongly developed than that at 0°. It would therefore appear that the upper surface of each lens of sand spreading into the basin from the north dipped to the south and was gently convex in an east-west cross section.

Each lens would therefore be thickest towards the northern end of the basin and about midway between the eastern and western margins. The greatest total thickness would therefore be found here provided that subsidence could keep pace with deposition. In fact the greatest thickness does occur in the Airth district which occupies just this position in the basin. Since all of the sediments are shallow water deposits it would appear that rate of subsidence was greatest here where load was greatest.

v) Orientation Pattern of Ungrouped Data.

The pattern of individual grain-vectors reveals several other interesting facts about the distribution. In the fine- and medium-grained sandstones the primary mode may resolve itself into 2 closely spaced maxima 15° or less apart (fig. 14a). In the parallel-bedded sands there is a single antimode 180° removed from the first pair and secondary maxima 90° away (fig. 14a). Where the parallel-bedded nature disappears the spread of the antimode increases. In the medium-grained cross-bedded sands the antimode separates into 2 modes (fig. 14b) which in one exceptional case (fig. 14c) are 90° apart. At the same time the secondary modes vanish completely and there are

2 distinct minima, one 90° on either side of the current direction (fig. 14c). In the coarser current-bedded sands the several modes occur throughout about a 90° arc so that there is a very large spread about the mean (fig. 14d) while the non-current-bedded sands have a distribution similar to the parallel-bedded sands but with a greater spread about the modes.

These various changes may again be explained by considering the grain as a truncated part of a cone with a small apical angle. Those grains with their broader ends upcurrent i.e. those forming the primary mode may pivot through an angle equal to the apical angle of the cone. If they rotate further then the current will impinge on one or other of the long sides of the grain and prevent further rotation. In this way the 2 closely spaced maxima of the primary mode develop. Since the grains in the antimodal class have their pointed ends upstream the current will impinge on both long sides when the grain is aligned parallel to the current and so there will be no tendency for rotation to occur. Also a grain lying slightly athwart the current will be rotated parallel to it because the current is striking only one of the long edges. There is thus no tendency towards bimodality in the antimodal group. The secondary modes in the parallel-bedded deposits are produced by grains rolling with their long axes normal to the current. Where the sands are current-bedded the grains are being deposited on a sloping surface. The sections examined were cut 11ℓ to this foreset slope. Very few grains will come to rest with their long axes normal to the current direction since in this position they are most liable to roll down the foreset slope swinging round as they do so, to lie in a more stable position. Grains with their broader ends upcurrent will as in the parallel-bedded sands be aligned parallel to the current. Where the position is reversed there is a tendency for the grain to rotate through 180° into the more hydrodynamically stable position. As it turns however, it becomes more liable to roll down the foreset slope, the broader end moving faster and so swinging the grain back to its original position. Equilibrium will be attained with the grain lying at an angle to the current and so the antimode becomes bimodal. The greater the current strength or the smaller the dip of the foreset slope the larger will be the angle through which the grain will rotate before equilibrium is attained. Eventually in the coarse sandstones where current strength and turbulence are considerable nearly all of the grains with their pointed ends originally upstream swing around so that the distribution becomes unimodal, the large spread about the mean being due to turbulence.

vi) <u>Persistence of Orientation</u>.

The area on which the orientation was measured was only about 1 sq. cm. of one bedding plane. It was deemed necessary to determine in how far the elongation direction varies laterally and vertically within a sample, to show whether in fact the orientation is controlled by the prevailing current or is greatly affected by such local variations as eddies. In the latter event no reliable conclusions could be based on the measurement of a single slide. The method of counting even single slides is already very time consuming and if several slides had to be counted to give a reliable mean for each locality then the method would be almost useless. The following comparisons were all carried out on parallel-bedded sands with a median grain size of about 0.2 mm.

The first comparison was of orientation patterns obtained from different parts of one slide i.e. from parts of the same bedding plane about 2 cms. apart. Fig. (15a) shows the result of one such comparison. It can be seen that here the modal group of the distribution is in the same position and the mean varies by less than 10° (Table No. 1). The minor features of the distribution are similar and the end effect is almost unchanged.

Comparative orientation diagrams were next prepared for thin-sections cut from the same bedding plane 10-12 cms. apart. Two such distribution pairs are shown in fig. (16 a & b). In the first of these the general form of the distributions are similar but there is some variation in the development of both primary and secondary modes. The mean azimuth has veered through 7° and the end effects are similar (Table No. 2). In the second the distributions are almost mirror images. The mean azimuth has swung through 177° so that while the current trend remains unchanged the sense is apparently reversed. Such a reversal was observed only once in 8 pairs of orientation diagrams but it does indicate that 'end position' is not an infallible guide to current sense in the fine sands. Here the end position can be affected by some factor other than the current, some environmental change which is present over a very short distance. The cause cannot be determined but it is suggested that it may be related to the form of the bottom. If, for example, the floor was covered in transverse ripples then the velocity of the bottom current and the most gravity stable position of the grain would be different on the lee and luff slopes of the ripple. No ripple marking was actually observed in the specimen.

In the third group of comparisons sets of 3 sections covering a vertical range of 10 cms. were considered - fig. (17 a, b, c). The samples used were massive and showed no apparent vertical change in grain size. In these, all the lesser features of the distribution vary considerably and the mean azimuth may swing through an arc of 25° (Table No. 3) or less in much the same way as do successive foreset units in the cross-stratified sandstones. The considerable changes in end effect probably reflect local or regional changes in current velocity during the deposition of the sandstone.

The data indicate that the mean azimuth of the modal groups remains sufficiently constant to be used to determine the general current trend. Local variation in 'end effect' measure is considerable.

vii) Current Circulation in Central and Midlothian Basins.

Composite diagrams of the current directions derived from cross-bedding, ripple marks, and grain orientation are shown in figs.

(18) and (19).

During deposition of the Lower Millstone Grit sands rivers entering the Central Basin somewhere further north than the present northerly extent of the Millstone Grit outcrop flow southwards into the basin. The southwards moving currents which they produce in the basin and which are most constantly observed along its eastern margin are locally deflected in the east of Clackmannan and replaced by westerly currents. The appearance of fluvial sands and gravels and of a slightly different mineral assemblage (P. 114) indicates that the deflection is the result of a delta growing westwards into the basin. The south-flowing currents are again deflected westwards in the south-easterly part of the Central Basin. This results from the influx of rivers from the south, rivers which drain the low positive area of the Lanark district and are responsible for the northerly currents and poorly-sorted fluviatile and 'dumped' sands of the lowest part of the Levenseat succession.

A greater complexity of current directions is observable along the western margin of the Central Basin. These may however be resolved into two distinct sets. The more obvious set is the west-flowing group: the remainder appear to radiate from a point about midway between Glasgow and Stirling, so that in the south-west, particularly around Glasgow, they are directed southwards while further to the north-east they flow almost due east. The rather different mineralogy (P 119) of this area suggests that the second set are the result of a delta complex advancing into the basin from the north-west. Explanation of the westerly currents is necessarily more tentative. Since however low positive areas existed at this time along the southern margin of the basin and probably also between the Central and Midlothian Basins the only apparent outlet from the basin is to the west and south-west of Glasgow around the northern margin of the Ayrshire volcanic plateau. There must therefore have been a flow of water towards this outlet which could produce the observed westerly-dipping current-bedding. Less probably the westerly flow could have resulted from saline bottom currents flowing towards the mouth of the north-westerly delta under the less dense fresh water currents discharged from that delta. Postma (1954, p. 46) has shown such a bottom flowage to exist in the Gulf of Paria.

The principal rivers providing the sediments of the Midlothian-Fife basin discharged into the north of that basin and from there the flow was southwards possibly towards an outlet to the south-west. There was a secondary influx from the positive area along the eastern margin of the basin.

The uniform south-flowing currents of the Upper Millstone Grit of the Central Basin result from the dominance of the northerly sources with weakening or disappearance of all others and from the submergence of the bar which formerly lay along the southern margin of the basin. The waters flow southwards over this now submerged area and are then probably deflected along the northern margin of the Southern Uplands into the Ayrshire Basin. There is probably still some egress to the west of Glasgow.

In the Midlothian Basin there is still a southwards flow from rivers discharging into the north of the basin with, along the eastern margin of the basin, a few westerly currents resulting from influx from the positive area to the east.

GRAIN-SIZE DISTRIBUTION

a) Technique.

A series of mechanical analyses was carried out in order to investigate the distribution of size grades and the variations of sorting within the Central and Midlothian Basins. The technique employed consisted of crushing about 50 grams of sandstone, treating it where necessary with dilute hydrochloric acid to remove any mineral cement, and separating into 11 grades using a series of standard Tyler $\sqrt{2}$ sieves, shaken in a Ro-Tap for 15 minutes. Since fine material of silt and clay grade normally constitutes less than 10% of the total material no pipette analyses were performed. In the few cases where it was important to determine the size distribution of the fine grades, this had to be estimated using a point-counter technique on a thin section of the sandstones.

There are several ways of expressing the results of these analyses in order to establish any regional trends in grain size distribution. The most common method is to use a set of parameters to represent median grain size, sorting, and skewness of the distributions and plot these parameters on a map (Krumbein 1938). The most satisfactory set of parameters, those covering the greatest part of the total distribution have been devised by Inman (1952). These are based on the 16th (ϕ 16), 50th (Md ϕ) and 84th (ϕ 84) percentiles of the cumulative size-frequency curve with the grain size in phi units ($-\log_2$ diameter in mm.) and approximate closely to moment measures wherever the distribution is not very skewed. The sorting co-efficient ($\sigma\phi$) is given by $\sigma\phi = \frac{1}{2}(\phi_{84}-\phi_{16})$ and the skewness ($\alpha\phi$) by $\alpha\phi = \dfrac{\frac{1}{2}(\phi_{16}+\phi_{84}) - Md\,\phi}{\phi} \simeq \dfrac{\alpha_3}{6}$ where α_3 is the moment skewness of statistics. Where the distribution is skewed towards the coarser material $\alpha\phi$ is negative. Conversely $\alpha\phi$ is positive when there is an excessive amount of the finer grades. A limitation of parameters is that they apply strictly only to unimodal distributions and hence are not applicable to markedly bimodal distributions (Van Andel and Postma, 1953). Nevertheless, they have yielded much useful information (as for example in A.P.I. Project 51) and have therefore been used in the present study. Another method is to classify the sediments into types depending on the shape of the cumulative frequency curve (Doeglas 1946, Van Andel and Postma 1953). This method has also been adopted and arithmetic probability paper used to enable comparison with the results of these workers. This paper has the advantage that a normal distribution will plot as a straight line, so that mixing phenomena can be easily distinguished by sharp bends to the left or sub-horizontal saddles.

Both vertical and areal variations of grain size distribution of the Millstone Grit sandstones have been studied. Ideally in a study of areal variation one should treat of a thin, well-defined synchronous bed. Unfortunately no such bed outcrops sufficiently often to be used in this present study. It has therefore been necessary to consider together a series of beds within which there may be appreciable vertical variation. It may be argued that this variation will vitiate the results of an areal study but it is here contended that provided there is random exposure of the various beds in the unit throughout the area under consideration then any observed regional trends will reflect a true areal variation in grain size distribution. Vertical variation may obscure existing lateral changes but cannot produce an apparent variation where none in fact exists.

Within the Millstone Grit two widely separated ranges were investigated. The first, a basal group, includes those sandstones between the Castlecary Limestone and No. 2 Marine Band which occurs some 50 feet higher except in parts of Clackmannan and East Fife where, in the presence of massive sandstone beds, this thickness may be more than doubled. The second group comprises the sandstones above the No. 5 Marine Band horizon. Hereafter these two groups will be referred to as the Lower Group and the Upper Group. Vertical variation is considerable in the Lower but only slight in the Upper Group (except for a few coarse grit bands).

b) <u>Distribution of Coarse Sands.</u>

Inman (1949) shows that there is likely to be an increase in the amount of coarse material shorewards in a marine environment or sourcewards in a fluviatile environment. The location of those sandstones containing more than 1% of material coarser than 1 mm. is shown for the Lower Group in fig. (20) and for the Upper Group fig. (21). From these it would appear that in early Millstone Grit times sources or shorelines were situated to the north of Clackmannan, to the west or north-west of Glasgow, along the south of the Central Basin in the

Levenseat area, and along the eastern and southern margins of the Midlothian Basin. The positive area to the south of Levenseat is probably an easterly extension of the "island" which covered much of Lanarkshire and Ayrshire at this time and is responsible for the absence or marked attenuation of Millstone Grit sediments in these areas. In the upper part of the Series there are even more coarse bands in Clackmannan, rather less in Midlothian and a complete disappearance of coarse material in the Glasgow and Levenseat districts where deposition has not kept pace with subsidence. The Lanark-Ayr positive area has been much reduced so that deposition is now occurring in the Carluke-Stonehouse district, but the presence of coarse sands to the south of Hamilton suggests that the positive area has not been completely overwhelmed.

c) Median Grain-Size.

The areal variation in median grain size of the sediments may be used to supplement the information regarding source directions deduced from the location of the coarse sands. It is to be expected that there will be a gradual decrease in competence of the transporting median away from source and so the material deposited will become gradually finer. Moreover if several sources are involved the major source may be expected to influence the grain size over a much greater area than any of the minor sources because it is carrying in a greater percentage of the total sediment . If there is a considerable influx from several directions regional trends may not be apparent.

There is a very gradual southwards decrease in grain size of the

Lower Millstone Grit sediments (fig. 22) from the coarse sands of east Clackmannan to the very fine sands and silts of the northern parts of Lanarkshire. A sharp rise in median grain size occurs in the Glasgow and Levenseat districts. It may therefore be inferred that the bulk of the material was being introduced into the north-east of the basin and spreading out southwards and westwards till it encountered material derived from rivers discharging into the basin in the Glasgow and Levenseat areas.

The few observations in the Midlothian Basin indicate that on the north of the Forth the sands are almost all medium grained with but a few coarser beds. On the south of the Forth there is a decrease through medium to fine sands suggesting once more a northerly inflow. The pattern is however, much complicated by the presence of very coarse sands which are prevalent along the eastern margin of the basin indicating another minor source to the east and south-east.

The southwards decrease in median grain size persists in the Upper Millstone Grit sands (fig. 23) and there is still evidence of a secondary source to the east of the Midlothian Basin but in the Central Basin there is a much less marked increase in grain size in the Glasgow and Levenseat areas suggesting that little if any material is still being introduced into these areas from secondary sources.

The valley of the River Avon affords a partial cross-section of the Upper Millstone Grit sands of the Central Basin. It can be seen that the grain size increases inwards from both east and west. The current strength must therefore have increased towards the centre of the basin and since it is found (e.g. Van Andel and Postma 1953, fig. 39) that competence and grain size decrease as the depth increases it may be postulated that during deposition of the Upper Millstone Grit sandstones, the east-west section of the bottom was gently convex, the depth increasing outwards until it started to shallow towards the coastline. Rather toc few observations are available for this inference to be more than very tentative.

d) Sorting.

In this discussion well sorted will be used to refer to sands in which the phi sorting measure σ is less than .50, moderately sorted where it is between .50 and 1.00 and poorly sorted where it exceeds 1.00.

Russell (1936) has shown that sorting may be divided into 2 types; progressive, and local. Where the depositional environment is unchanged over a wide area then the material being deposited becomes progressively better sorted away from source. Where there is a local change in environment such as a sharp increase or decrease in depth then there is a consequent rapid local change in sorting. If there are numerous local sorting effects then the progressive sorting pattern will be obscured.

Local sorting is important in the Lower Millstone Grit sands but it may be observed (fig. 24) that there is a very gradual southwards and westwards improvement in sorting from an area of poorly sorted sands in Clackmannan. Throughout almost the whole of the Central Basin the sands are never more than moderately sorted but in the

Linlithgow area there is an excellent example of 'local'sorting with the abrupt appearance of very well-sorted sands. Equally abrupt deteriorations in sorting occur in the south-east and extreme west of the Central Basin. It would therefore appear that the bulk of the sands entered the Basin in the Clackmannan area, spread outwards to south and west, and were little reworked after deposition anywhere except near Linlithgow where rapid shallowing occurs. There was also a sudden change in environment around Glasgow and Levenseat. The well-sorted sands of Fife pass southwards into an area of poorly sorted sands in Midlothian, the rapidity of the change suggesting that it is due to an influx of material rather than to increase in depth.

The Upper Millstone Grit sands are much better sorted (fig. 25) than those of the Lower part of the Series. The extensive reworking necessary for the production of such sorting is most likely to have been attained in a basin of very shallow water in which there were few bars to free circulation. On the west side of the basin in particular the progressive southwards sorting indicates the northerly derivation of the sands. An area of moderate sorting is coincident with the gentle anticline along the crest of which the River Avon now flows and there are still slight deteriorations near Glasgow and Levenseat. A much more marked rise in the sorting co-efficients in Lanarkshire reflects even greater restriction in current circulation but southwards again as this bar is passed the sands are again sufficiently reworked to be well-sorted. The well sorted sands of Fife and the centre of the Midlothian Basin are again flanked to east, south and west by poorly sorted material.

e) Skewness.

The exact causes of skewness have never been determined and it has therefore been used only infrequently. Inman (1949) suggests that plots of skewness against median diameter go through several cycles with very coarse sands skewed towards the finer grades, coarse sands towards the coarser grades, fine sands almost symmetrically distributed, and very fine sands towards the finer grades once more. Now in the Lower and Upper Millstone Grit sands the median size is almost identical yet the mean skewness values are much higher for the Lower group of sands. In Stirlingshire for example the mean skewness is 0.28 for the Lower Millstone Grit and 0.10 for the Upper Millstone Grit yet the mean of the median diameters is almost identical. It is therefore possible that skewness considered together with median-grain-size may afford some clue to environment. This possibility will be discussed later in this section.

f) Distribution Curves.

The significance of the shape of the size distribution curve of a sediment was first investigated by Doeglas (1946) who discussed the derivation of various types from rather poorly sorted parent material - curve c of (fig. 26a). Where the current velocity becomes so low that all material coarser than 0.34 mm. settles out the size distribution of the particles still in suspension may be computed by recalculating that part of c below 0.34 mm. to 100% (curve t_1): t_2, t_3 and t_4 are the distributions of the suspensions remaining when everything above 0.20, 0.12 and 0.05 mm. has settled out. On the other hand if c is a bottom sediment from which the increased current velocity removes all material below 0.34 mm. then the distribution of the residual material is given by curve r. When the velocity decreases again everything above 0.2 mm. may settle out to give the distribution s. Fluctuation in current velocities will render these curves almost straight.

Van Andel and Postma (1953) also studying size distribution curves in different environments used types rather similar to Doeglas's curves. The F type, the coarser member, was equivalent to c and r curves; M and S intermediate differentiates similar to s and t curves; C the finest rest suspension. In addition they introduced a B type of coarse very poorly sorted material. Combinations of the various types were also recognised.

The F type was found to be typical of areas where the river regime was dominant. An association of M, S and M-S types occurred in the lower delta, on the delta platform, and in estuaries. M types with a sharply defined maximum and minimum size are produced on wave-swept beaches. B-C and B-S types represent material dumped close to source. A mixture of M-C and M types is found in shallow marine environments or lacustrine (i.e. in platform sands). C types occur in open marine areas and elsewhere where there are only very weak currents far from the source of the material.

The curves recognised in the present study are similar to those of Van Andel and Postma with a few additions. A common type of distribution in the Millstone Grit sands is intermediate between F and M_1 types. This has been designated FM, and may be expected to occur in an area of strong currents where no very coarse material is available. Another type more common in the underlying Upper Limestone Group than in the Millstone Grit itself is the W - type distribution. This distribution curve is convex upwards with the fairly well marked bend in the curve occurring at about 0.2 mm. Inman (1949) (fig. 26) has shown that sand about 0.2 mm. in diameter is more easily moved than either coarser or finer material. If therefore a bottom sediment of F-M or F type is subjected to a non-turbulent current with a velocity of about 2 cm/sec. then most of the material winnowed from it will be about 0.2 mm. in diameter and the resultant curve for the residual sediment will be of W type. To build up a thickness of sand of this type would require a periodic variation in current velocity such as might be expected to occur as a result of tidal variation in a shallow marine environment. Its common occurrence in the Upper Limestone Group sands serves to confirm the view that this is a shallow marine type. The M type curves frequently have a very small 'tail' of coarse material: where this is very prominant the prefix B has been used e.g. BM_2. Typical curves and zone diagrams of the various types are shown in (fig. 27) the corresponding parameters in Table (3).

In the Lower Millstone Grit (fig. 28) there is an area of F, FM and B types in the south-east of Clackmannan; therefore in this area the environment must have been largely fluviatile with some erosion of nearby sediments to produce the B curves. This same 'cannibalism' is responsible for the fragments of mudstone which are often found embedded in the grits (Plate 1). To the west and south of this area are platform sands of M, C type. This shallow water platform on which increasingly fine M-C and M-S types were being deposited extends south westwards towards Glasgow where a sudden reappearance of F and B types indicates that another nearby source was being eroded and that there was another inflow in this area. On the east side of the snycline platform types are found in the Boness area but southwards towards Linlithgow there is a sudden very marked improvement in sorting, and M types with sharply defined maximum and minimum size i.e. beach types are found together with very shallow marine W type. These stretch southwards for 3 miles before they are replaced by MS types. Fluviatile influences and 'dumping' are again in evidence along the south-east margin of the syncline near Levenseat. They rapidly give way northwards to M and MS types typical of a delta platform. Outwith the Central Basin and to the south of the Ayr-Lanark 'island' shallow water M types with a few F sands are present around Douglas. Similar F, M, and M-S types extend westwards into the Ayrshire Basin.

That part of the Midlothian-Fife Basin north of the Forth is occupied by deltaic FM and M sands. In Midlothian however these types are associated with coarse B and F types. It would appear that this coarse material is being derived from a nearby easterly source and dumped where the rivers disgorged into the shallow-water basin.

The fluviatile influence was still dominant among the Upper Millstone Grit sands of Clackmannan (fig. 29). The rivers were more mature than formerly and so B types are now absent. The persistence of FM types along the west side of the basin would seem to indicate that very shallow water conditions persisted south towards Lanarkshire with a stronger inflow from the N.N.W. than in the early Millstone Grit. The succession from F through M to MC types in the Avon valley on the east of the syncline suggest increasing depth away from the centre of the 'basin'. Moreover the presence of fluviatile types are far south as this, indicates that the shoreline sometimes migrated well south into the basin. The thick succession of F FM and M sands covering the northern half of the basin has resulted from a series of sheets of sand spreading rapidly into the area from the north with the shoreline migrating back and forth depending on whether subsidence or deposition was more rapid. The well sorted M types covering the rest of the Central Basin are indicative of very shallow water conditions on a delta platform with vigorous wave action reworking the deposits and removing the finer material. In Lanarkshire where previously there had been land there was now an area of platform or tidal-flat sands of MC type with a few BC types to suggest that some local erosion still continued. Southwards again are the M sands of a very shallow marine area.

Conditions in Fife were similar to those in the Central Basin and there are also many M type sands in the axis of the Midlothian Basin but F, FM and B types along the east margin indicate that rivers were still flowing into the shallow basin from the east. In the Joppa area and elsewhere of the west of the basin are the MS and S types of an area of weaker currents. The thin coals and ironstones in the succession indicate that this was not an area of deeper water but rather shallows over which the currents of the main basin are not operative.

g) <u>Relation between Parameters and Curve Types.</u>

When all save B type distributions are considered it is found that in the coarser arenaceous deposits there is a gradual improvement in sorting with decreasing median grain size so that σ falls from over 1.0 at 0.6 mm. to 0.4 at 0.18 mm. Thereafter it begins to increase till it again exceeds 1.0 at 0.12 mm. It is therefore apparent that the current velocity is an important factor in determining the degree of sorting. As Inman (1949) has shown, the range of size grades which can be moved by bottom transport decreases with current strength till with current velocities of less than 2 cm/sec. only fine sand with a median diameter of .18 mm. can be moved so that sorting improves with decreasing current strength. With weak currents where there is little turbulence most of the material is derived from suspension and since all grades are settling, albeit at different speeds, the sorting deteriorates. Since the sorting co-efficient begins to increase rapidly where the median falls below about .135 mm. it may be assumed that material with a lower median grain-size is derived entirely from suspension as bottom currents are no longer strong enough to transport the grains. It was at just below this median grain-size that preferred orientation disappeared (P. 54). This also suggested the disappearance of effective bottom currents.

Current velocity probably controls the median grain size but it is not the prime control of sorting. In the M and MS type sands for example the sorting is almost constant at about .40 while the median varies from 0.35 mm. to 0.13 mm. In MC types covering the same range the sorting index increases steadily from .50 to .95. The degree of sorting is probably controlled largely by the amount of turbulence, which is itself only partly dependent on current velocity, and more by the amount of reworking of the sediments. The lower the turbulence the greater would be the range of sizes which would settle. The sorting index would also be higher where the time or degree of reworking was less. There is no reason to suppose that the MC sands, associated as they are with mudstones and shales were deposited more rapidly than the dominantly arenaceous Upper Millstone Grit M types. The cause of the poorer sorting of the MC types is therefore less vigourous reworking. Effective wave action and turbulence decrease with increasing depth in a shallow marine environment and it therefore seems possible that for a fine sand the degree of sorting is as much a function of depth as of distance of transport. This hypothesis would seem to be supported by the results illustrated by Inman (fig.30). Beach sands from two localities have a sorting index of about 0.25;

in the shallow marine Cape Cod Bay σ has risen to 0.50 while in the much deeper Red Sea samples it has increased to 1.25. The results of Holzman (1952) also indicate that for a given size of medium to fine sand the sorting deteriorates with depth. If, as seems possible, the above values are usually approximated at the same depth then it would appear that there was an area of beach sands in the Linlithgow area in the Lower Millstone Grit and that over much of the Central Basin shallow marine conditions prevailed. The Upper Millstone Grit sands of the Central Basin and nearly all of the Fife sands were deposited in an extremely shallow water area. This method of estimating depth can only be used with shallow marine M, MS and MC type sands. It cannot be used with fluviatile types which of course themselves indicate very shallow water nor with dumped B type sediments where the material has been deposited much too rapidly for wave sorting to have been effective. The variation of sorting with grain size for the different distribution types i.e, for different environments is shown in fig. (31). It can be seen that the B types i.e. those with dumped material are equally poorly sorted whatever the grain-size.

The skewness co-efficient (fig. 31) is much more sensitive to changing grain size than is σ. The F type sands with a median grain size of just over 0.5 mm. are an almost symmetrical but with decreasing grain size the sands become increasingly skewed towards the coarser grades till at 0.32 mm. the skewness is about - 0.20. Thereafter the skewness again begins to decrease. Presumably therefore in the coarse sands the turbulence is sufficient to keep much of the finer material in suspension while the really coarse material, by virtue of its larger diameter, is in a field of fast flow and once moving has sufficient impetus to keep it rolling. It is therefore largely removed (Gilbert 1914). As the current velocity decreases this second factor becomes less important and therefore the sands become increasingly skewed towards the coarser grades. Below 0.32 mm. the decreasing turbulence puts less of the finer material into suspension and so the distribution becomes more symmetrical once more.

The FM, M, and MS types, because they occur in the same type of environment, form a continuous series in which the skewness rises irregularly from 0 at 0.3 mm. to about .25 at 0.175 mm. and thereafter tails off till the distribution again becomes symmetrical at 0.125 mm. The same pattern with a maximum skewness at 0.175 mm. is observed in the MC sands which are however much more skewed towards the finer grades. Because of the lesser turbulence in the marine environment and because of the reworking effect of wave action the FM, M and MS types have symmetrical distributions at the same grain size at which the fluviatile types were most strongly skewed towards the coarser grades. As the velocity of the bottom currents decreases in this shallow marine environment the amount of finer material derived from suspension increases and so the distribution becomes increasingly skewed towards the finer grades. Eventually however the current velocity becomes so low that more material is being derived from suspension than from bottom creep. Where previously the distribution consisted of much sand with a median diameter of about 0.18 mm. together with ever decreasing amounts of finer grades so that there was a strong skewness towards the fine grades, now the mean falls in the grades derived from suspension with lesser amounts of finer material but also with coarser grades moved by bottom creep so that the distribution is again more symmetrical. When bottom movement ceases completely the sands will again become skewed towards the finer grades.

The F, M and MS, and MC types represent 3 environments in which there is an increasing tendency for skewness towards the finer grades. This phenomenon may be interpreted as resulting from variations in turbulence and reworking. Turbulence is much greater in the fluviatile environment of the F types than in the marine conditions in which the other types were deposited. Less finer material would therefore be derived from suspension in the fluviatile environment and hence there is least tendency for skewness towards the fine grades in F types.

Part of the finer material deposited in the marine environment may be removed by reworking of the sediments. Since the MC sands are more strongly skewed towards the finer grades than the M and MS types they have been less reworked than these types. Again as with sorting the degree of reworking by wave action decreases with depth or with greatly increased restriction of the environment. Increasing positive skewness therefore implies first a change from fluviatile to marine environment and then increasing depth or restriction of that marine environment.

For medium or fine sands a negative skewness is considered to indicate a fluviatile origin, low positive skewness, below about .25 open shallow water conditions and high skewness either deeper water, rapidly dumped material, or a shallow environment in which there are numerous bars to inhibit free oscillatory current movement.

Using these criteria it is found that skewness maps of the Lower and Upper Millstone Grit (figs. 32 and 33) afford the same environmental picture as do the other parameters.

h) Vertical Variation in Parameter and Curve Type.

The vertical variation in grain size distribution has been studied in detail in core specimens from a bore just north of Kincardine supplemented by specimens from the nearby coastal section to represent that part of the succession missing, by faulting, from the core. The vertical variation has also been examined in less detail in a traverse in the Levenseat district and on the coast at Port Seton and Pathead in the Midlothian-Fife Basin.

At Kincardine the sands below No. 1 Marine Band are poorly sorted fluviatile types with a few shallow water M and BMC types 25 ft. above the Castlecary horizon at about the point where No. 0 Marine Band would normally be expected to occur. In this basal part of the series deposition has kept pace with the gradual subsidence but above No. 1 Marine Band there is a recession and fluctuation of the shoreline so that moderately sorted FM, BM, M and MC nearshore shallow water types occupy the succession to a point 40 feet above No. 2 Marine Band where the MC sands give way to a thick series of shales and siltstone which persists until after the formation of the next marine horizon. At several horizons with this range, notably just below No. 2 and No. 3 Marine Band limestones thin coals occur denoting silting up of this part of the basin. Fine platform types indicative of continued slow deposition occur above No. 3 Marine Band Group but soon give way to delta front M types which extend upwards towards No. 5 Marine Band Group becoming gradually better sorted as an area of very shallow water is established. Within the Marine Band Group itself are deltaic and fluviatile sands. The succeeding M sands are intercalated with fire-clays and thin coals showing that the area remains almost at sea level. Such strata extend upwards to include No. 6 Marine Band Group which again has coarse fluviatile sands within it. The rate of subsidence and deposition increase so that the top 200 feet of the series consists of massive, well sorted shallow water M type sands interspersed with a few coarse fluviatile horizons resulting from more rapid influx of debris with consequent extension of the fluviatile regime.

The general sequence of events in the area seems to have been elevation from the shallow marine W and MC types of the Upper Limestone Group to give an area of rapidly deposited, fluviatile sands, slow subsidence and an ever decreasing rate of deposition with frequent silting up of the basin of deposition and finally more rapid deposition of deltaic and fluviatile sands which are succeeded by the slack-water MC types of the Coal Measures.

The same pattern of basal fluviatile sands followed by a period of much slower shallow-water deposition and then by a recurrence of coarser types interspersed with delta-front types is found at Port Seton and elsewhere in the Midlothian Basin and 200 feet of shales occur in the middle of the thick series of M and F sands in Fife.

In the Levenseat area coarse B and F types of southerly derivation are mingled with fine shallow-water sands. The coarse sands quickly disappear but drifted logs presumably from this same nearby positive area are found above No. 2 Marine Band horizon. Fireclays, shales, and fine platform sands occupy the next part of succession but above the lateral equivalent of No. 3 Marine Band fluviatile and coarse 'dumped' material reappear as a result of uplift to the south of the Central Basin at this time. These coarse sands are again quickly replaced by the moderately well-sorted, delta-front sands of northern derivation which occupy the rest of the succession.

The general pattern of movement seems to commence with uplift of the whole of the Midland Valley with emergence of the northern part and also of areas in Lanarkshire and East Lothian. The fast-flowing rivers draining these areas dump their coarser material close to shore and spread rather ill-sorted material over the rest of the basin. As the whole area gradually subsides the smaller positive areas dwindle. The rivers are also more nearly at grade and so there ensues a prolonged period of slow deposition in a shallow water area with occasional silting up, particularly of the northern part of the Central Basin. Eventually there is a further series of uplifts of the north of the Midland

Valley and possibly of the still more northerly sources, rejuvenation of the rivers, and the development of a series delta lobes encroaching southwards.

i) <u>Significance of the Differences Between Lower and Upper Millstone Grit Sandstones</u>.

It has been shown that differences do exist between the parameters of the Lower and Upper Millstone Grit sandstones. Are these differences such that the 2 sets of observations might be drawn from the same population by random sampling or must they be drawn from different populations, that is, do they really represent different environments of deposition? How stable was the environment at both periods?

In order to resolve these problems the Central and Midlothian Basins were arbitrarily divided into 10 sections, the data for each section being statistically analysed. Since the samples were small the t test of significance was adopted. If we have N_1 readings of variable X_1 and N_2 readings of variable X_2 and we wish to decide whether the means $\overline{X_1}$ and $\overline{X_2}$ differ significantly from one another we need 6 quantities N_1, N_2, $\sum(X_1)$, $\sum(X_2)$, $\sum(X_1^2)$ and $\sum(X_2^2)$. Then $\overline{X_1} = \frac{\sum(X_1)}{N_1}$ and $\overline{X_2} = \frac{\sum(X_2)}{N_2}$. The variance of the combined observations is given by $\sigma_d^2 = \frac{\sum(X_1 - \overline{X_1})^2 + \sum(X_2 - \overline{X_2})^2}{N_1 + N_2 - 2}$ and the standard error of the difference is equal to $\sigma_d\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}$

t in this case is the ratio of the difference between the means to the standard error of that difference i.e. $t = \frac{\overline{X_1} - \overline{X_2}}{\sigma_d\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$

From the values of t and n (which is $N_1 + N_2 - 2$) we may, from a set of tables (Fischer 1948 p. 174) derive the probability P of the significance of the difference. Where $P < .05$ it is almost certain that the differences are significant.

If the environment remained absolutely unchanged during deposition of all the sandstone members of each group then every one would have the same parameters. The greater the change in environment the greater will be the variation in the parameters. The most useful measure of scatter is the Standard Deviation $\sigma = \sqrt{\frac{\Sigma(X - \bar{X})^2}{N}}$. To compare the scatter of different variables about their means it is often useful to express the scatter in a form independent of the absolute size of the variables. This is done by use of the Co-efficient of Variation $V = \frac{100\,\sigma}{\bar{X}}$ which is independent of the units in which the mean and standard deviation are calculated. Whether the Standard Deviation or the Co-efficient of Variation will afford the most reliable indication of the degree of environmental variance depends on whether the same amount of change of environment will produce the same absolute or relative change in a parameter i.e. if a change alters a parameter from 10 to 20 will the same change alter it further from 20 to 30 (Standard Deviation) or to 40 (Co-efficient of Variation). Both measures have therefore been used, save in the case of skewness where the positive and negative value render V useless.

Tables (4, 5, 6) contain the results of this statistical investigation.

When the Median Grain Size is considered it is found that no significant difference exists anywhere save in the Linlithgow area where the Upper Millstone Grit sands are finer. This lack of disparity is due in part to a sampling bias since no sediments finer than sand grade were examined. Had the associated shales and clays been taken into account it is certain that over most of the area the Lower Millstone Grit sediments would have had a lower median size. When the range in size is considered (fig. 34) it appears that there were very marked variations in current velocity in the Glasgow area and in Midlothian and considerable fluctuations also in Clackmannan and near Levenseat during the deposition of the basal sediments. At the same time a very stable environment exists in the Linlithgow district and in the Fife basin. The Upper Millstone Grit currents were much more constant, moderately high fluctuations occurring only in Clackmannan and Midlothian. In only 2 areas, West Lothian and Fife, is there not a drop in the measures of scatter. The case of Fife is particularly interesting for it would appear both from the median size and from the other parameters that the stable deltaic conditions which appear only in the upper beds of the Central Basin were to be found at both top and bottom of the series in Fife, the Lower Millstone Grit environment being slightly the more stable of the two.

The same pattern of relative instability in the Lower Millstone Grit of the Central Basin with considerable variations in environment in Midlothian, Glasgow, Levenseat and Clackmannan is manifest in the sorting and skewness parameters (figs. 35 and 36). It also appears that there were appreciable variations along the east side of the syncline in West Lothian and there is a wide range of sorting in the thin Upper Millstone Grit sands which cover the area of Lower Millstone Grit emergence in Lanarkshire.

Significant differences in sorting occur in Clackmannan, along the west side of the Central Basin in Stirling and Dumbarton and down the east side in West Lothian. Significant skewness differences occur in the first two of these areas and also in the Linlithgow and Douglas areas.

It is therefore apparent that the environments of deposition of Lower and Upper Millstone Grit must have been different in the Central Basin but were possibly similar in the Midlothian-Fife Basin. That significant differences in the parameters are not observed in the Glasgow and Levenseat areas is due to the high standard deviations found in these areas where P has a value between 0.1 and 0.2.

j) Significance of Areal Differences.

Since the study of the areal variations in the grain size parameters was carried out on two discrete successions of limited vertical extent rather than on the ideal thin isochronous layer of sandstone the regional trends which have been discussed in the foregoing section are obscured to a greater or lesser extent by local patchiness. In order therefore that these trends should have a basis more objective than inspection the same statistical tests applied to the Lower-Upper Millstone Grit comparison have been adopted. Such a map (figs. 22a-25a, 32 and 33a) accompanies each of the areal variation maps. Where the variation between adjacent areas is significant this is indicated by an arrow linking the areas.

The median grain size of the Lower Millstone Grit sands decreases rapidly southwards so that is significantly lower in both Stirling and West Lothian. At the same time the sorting shows a significant increase in Stirling but deteriorates slightly in West Lothian exclusive of the Linlithgow area where the sands are very markedly better sorted than in any other part of the basin. Therefore the sands are becoming finer away from the Calckmannan delta with the sorting improving where there is considerable wave-reworking in shallow water and especially on the beaches of the Linlithgow area. That the sediments are poorly sorted in West Lothian is the result of deposition in calmer deeper waters. The areas in order of increasing depth would be Linlithgow, Clackmannan, Stirling and West Lothian. The skewness does increase in this order and it has already been suggested that increasing skewness does accompany increasing depth. Where the water shallows again to the south of West Lothian the sorting improves, the skewness decreases, both by a significant amount. The increased grain size resulting from influx of coarse material from the south is well marked.

The sands of the western part of the basin are also significantly coarser and less skewed. Another influx into this area may therefore be postulated, the poor sorting resulting from rapid deposition with little reworking because of the largely fluviatile environment.

In the Midlothian Basin no significant differences were observed, but in Midlothian, as a result of local influx of material the sands are coarser and less well sorted than they are across the Forth in Fife.

In consequence of the much more uniform current velocities prevailing during deposition of the Upper Millstone Grit sands the only significant difference in grain size which can be shown to exist between adjacent areas is in the extreme west of the Central Basin where coarser sands are still deposited. The sands do become slightly finer southwards however and are significantly finer at Levenseat in the south than they had been in Clackmannan.

Sorting again improves away from the Clackmannan and Glasgow delta fronts, the improvement being most rapid along the shallower western part of the basin where the Stirling sands are significantly better sorted than most others. Sorting index and skewness still increase in the deeper southern part of the basin. Elsewhere in the now shallow basin the skewness is very low. In the very restricted environment of the now partly submerged southern bar the sorting and skewness are significantly worse than elsewhere.

Local influxes and a comparatively restricted environment result in significantly poorer sorting in Midlothian than in the shallow delta front sands of East Fife.

k) <u>Roundness and Sphericity</u>.

The shapes of the grains were assessed in terms of 'roundness' and 'sphericity' (Krumbein and Pettijohn 1938) using the Visual Estimation Charts of Krumbein (1941, p. 68) and Rittenhouse (1943, p. 80).

From the areal variation in roundness in the Lower Millstone Grit (fig. 37) it would appear that the degree of rounding increases in the direction of transport for the lowest roundness values are found in the areas of influx of material, that is, in Clackmannan, Glasgow, and Midlothian and to a lesser extent at Levenseat. Away from these areas the rounding increases rapidly probably as a result of rapid change of environment but over most of the rest of the Central Basin the roundness is fairly constant. The values for the Upper Millstone Grit are both higher and more constant (fig. 38). It seems that abrasion will rapidly round angular grains but where the roundness co-efficient increases above .40 then it requires very much more transport and reworking of the grains to produce a greater degree of rounding in an aqueous environment. Even the supposed beach sands of the Linlithgow area have only this order of rounding.

That roundness is not entirely dependent on the pre-depositional history of the grain is evident from the area of low roundness West of Lanark (fig. 38). Here the low roundness co-efficients are due to corrosion of the grains by the clay matrix (Plate 6). Similar post-depositional changes are also produced wherever there has been appreciable secondary growth of the quartz grains such as is common in orthoquartzites.

The mean roundness of the Lower Millstone Grit samples was .32, and of the Upper Millstone Grit .41. Applying the t test of significance (P. 86), it was found that $P < .05$ and thus it may be said that the roundness differs significantly in the same way as did the grain size parameters. Therefore while the degree of roundness does not reflect only the distance of transport it does change with changing environment because such factors as the amount of clay matrix which produce diagenetic changes in roundness are controlled in the first instance by the depositional environment.

The sphericity showed no areal variation and did not differ significantly between Lower and Upper Millstone Grit sands. In both it varied between .70 and .80 with a mean of .75. It also proved impossible to correlate sphericity with the median size of the sediment and it is therefore suggested that sphericity is controlled by the original shape of the quartz grain and hence by the type of source-rock rather than by either the distance or mode of transport. This conclusion accords with the findings of Pettijohn (1949, p. 54) who found that only slight shape modifications were produced by abrasion.

1) Millstone Grit Rhythms.

Rhythmic sedimentation is a common feature of the Millstone Grit succession, the general sequence of rock types being:

a) Coal

f) Fireclay

e) Siltstone or Mudstone

d) Sandstone

c) Mudstone

b) Calcareous shale with *Lingula*, *Productus*, fish scales and crinoids

a) Coal

The full sequence for the similar Coal Measures rhythm is (Robertson, 1948, p. 150)

a) Coal

m) Fireclay } with ironstone nodules
l) Mudstone }

k) Sandy Mudstone

j) Sandstone

i) Grit or Pebbly Sandstone

h) Sandy Mudstone with plant impressions

g) Mudstone with *Carbonicola*

f) Shale with *Anthracomya* and *Naiadites*

e) Shale with fish remains, *Estheria*, and Ostracods

d) Shale with *Lingula*, *Orbiculoidea*

c) Calcareous shale with goniatites, gastropods, brachiopods & fish

b) Cannel with fish remains

a) Coal

Formation of such a rhythm has commonly been ascribed to intermittent regional subsidence or to alternating periods of rise and fall of the crustal block with predominating subsidence. That such oscillatory movements of just the right magnitude could have occurred during the formation of each of several rhythms seems unlikely. Robertson (1946) rejects these mechanisms and suggests that there is steady subsidence of the crustal block, the rhythm being due to the differing rates of compaction of the different sediments. The rate of compaction is greatest during formation of the coal swamp because of compaction of the underlying fireclays. At this time the influx of sediment is inhibited by vegetation and the sea is dammed back by an offshore bar.

Eventually this bar is breached and there is a rapid marine incursion with a transition to fresh water conditions when the barrier reforms. It is suggested by Robertson that the barrier which is broken may be a levee of the seaward reach of the main distributary channel though it is not explained how this could produce a marine incursion; unless the sea were already dammed back completely by a bar, marine conditions would exist before the levee broke. Above stage g) influx of detritus from rivers begins once more. The suggestion that muds are deposited first because they travel more rapidly than sand is not convincing: grain-size depends on current velocity at the site of deposition rather than on the relative speed of transportation of different grades of detritus. Silting up and formation of the next coal seam complete the rhythm.

The essential features of the rhythm are the variation in grain-size of the detrital material, and the formation of a calcareous horizon and an occasional thin coal. Since the same sequence is observed over and over again it would appear that all three of these features are interdependent or are controlled by the same factors.

The grain-size of the deposits was entirely controlled by the velocity of the currents in the depositional basin. These were in turn dependent, particularly in the almost land-locked basins of Millstone Grit sedimentation in the Midland Valley of Scotland, on the speed and volume of water being discharged from rivers. There must therefore have been a rhythmic variation in the flow of these rivers which affected the grain size of the deposits for two reasons. First, when flowing slowly, the river could only carry fine material into the basin: second, the retardation of currents in the basin permitted of the deposition of that fine detritus. Flow was at a minimum at stage (a) of the Millstone Grit rhythm and at a maximum during deposition of the sandstone member (d). At the time of minimum discharge evaporation within the basin would be greatest because the temperature of the more slowly moving water would rise since the same volume of water would remain in the basin for a longer time. Moreover, evaporation would be assisted by the vegetation of stage (a). Whenever the loss by evaporation exceeded the inflow from rivers the salinity and concentration of other salts in the enclosed basin - lake or lagoon - would increase. This concentration reached a maximum some time later than the period of minimum flow, just before the influx again began to exceed the loss by evaporation. At this time a fauna adapted to a saline environment could spread into those parts of the basin where at other times the water was too fresh. The result is the shale stage (b). The solubility of calcium carbonate was also frequently exceeded at this time. On the amount of this excess depended the amount of calcite precipitated in the shale. The concentration of salts would obviously be much lower near the mouths of the main distributaries. These calcareous shales with a marine fauna are therefore often missing in such areas e.g. in Clackmannan. A minor factor controlling precipitation of $CaCO_3$ was the temperature. Where this was highest (stages f - b) the solubility of $CaCO_3$ was lowest. The increase in salinity to a maximum and its gradual decrease can be seen to have affected the fauna of stages (b) to (g) of the Coal Measures rhythm. Where the rhythm was, if ever, being formed in a shallow open marine area then increased salinity still results from decreased inflow of fresh water (Van Andel 1954, figs. 12 and 14). There would be no outflow from the basin during and prior to the formation of a calcareous shale when evaporation exceeded influx and therefore no transport of material into another basin. This may account, in part, for the apparent unconformities within the Ayrshire basin where much of the detritus may have arrived from the Central or Midlothian Basin.

The variation in grain size of the detritus and the formation of limy bands can be accounted for by variation in the discharge from rivers. The possible causes of this discharge variation include uplift of the source area, changes in precipitation, variation in loss by evaporation during transport and the confinement of the main outflow within distinct channels with slack water between, as a result of silting-up of the basin.

Periodic uplifts of the source may sometimes have been a factor but they would not normally be expected to produce the rather gradual increase in grain size of the normal rhythm. A cyclic variation in rainfall cannot be discounted: neither can it be shown to have existed. If it did exist it would affect not only the initial amount of water falling into the catchment area but also the luxuriance of the vegetation and hence the losses by evaporation during transport. Such losses can be very great; over 90% of the total flow of the Nile is at present lost in this way at certain seasons of the year. It is considered that the rhythmic flow was controlled by the vegetation which need not however have varied with precipitation. A river flowing a comparatively short distance from a mountainous source will carry sand down into the basin of deposition and gradually form a delta. On this low fan ever increasing amounts of vegetation will develop. These plants greatly increased evaporation in the delta region and also partially blocked the distributaries. As a result much of the coarser sand was deposited before it reached the main basin and so within the basin the grain size became finer. Eventually almost no sand was reaching the basin. Decaying vegetation floated into the basin to form the basis of the parrot coals with high mud content which are often the representatives of stage (a) of the rhythm. In the delta areas the coals formed in situ with a rootlet bed below. If the basin is above sea level or completely cut off from the sea then, because of the high rate of evaporation the water level falls, large mudbank areas are exposed and on them develop vegetation which decays to produce autochthonous coals. It is in these ways that the coals of the Millstone Grit rhythms are thought to have developed. In other cases the delta continued to grow in a birds-foot pattern, the main distributaries were enclosed by levees and in the inter-distributary areas coal swamps developed. The fall in the amount of debris from a distant source which was entering the basin at these times affected the heavy mineral assemblage of the Millstone Grit sands. Locally derived garnetiferous material became relatively more abundant.

Three factors combined to end the coal-swamp phase and to reestablish normal detrital sedimentation. First, over the submerged parts of the basin the concentration of salts became so high, prior to precipitation of $CaCO_3$, that vegetable growth in these areas was checked, then retreated as the area of high salinity increased. This retreat was assisted by the gradual submergence of the delta areas as subsidence proceeded more rapidly there, than in other parts of the basin because of the greater load. At the same time the base level had fallen in the basin as a result of evaporation, so that there was an ever increasing tendency for streams, flowing more rapidly in their upper reaches, to break into the basin. This factor can only operate in a closed basin such as the Central Basin and may not be always necessary. Break-down of the vegetable barrier by streams and by advancing saline waters was gradual. As the inflow exceeded evaporation, salinity fell, the marine fauna was replaced by brackish then fresh water forms and the base level rose as the basin was filled once more. Flooding of the delta region became more rapid, the vegetable barrier broke-down completely, and the sands dammed up behind it were again swept into the basin. Where flooding was very rapid the sands were swept in sufficiently quickly to produce the scouring which may often be observed at their base. A sand delta was again formed on which vegetation again spread and the rhythm was repeated.

On occasion, the barrier of vegetation and levees was breached suddenly when the base level was low. When this happened coarse sands dammed up behind the barrier poured into the basin until the breach was repaired. Such coarse fluviatile type sands are quite commonly present within the marine band groups of the Scottish Millstone Grit.

HEAVY MINERAL ANALYSIS

a) Technique

i) A sufficient quantity of each sample was crushed in an iron mortar until the individual grains had been disaggregated without being fractured. The same technique was used in every case since it has been demonstrated (Tyler and Marsden, 1937) that differences in crushing procedure can produce significant differences in the relative abundance of the various heavy minerals. The disaggregated material was then screened and that portion which was retained on the 0.5 mm. Tyler sieve was rejected. This limiting size was chosen after several preliminary separations carried out on unscreened samples of coarse and medium grained sandstones had revealed that the mean diameter of the heavy mineral grains was just over 0.2 mm. while only .08% of the 2500 grains examined would have been retained on the 0.5 mm. sieve. Where a calcareous or ferruginous cement was present this was then removed by boiling with a 20% solution of citric acid. This organic acid was chosen because it does not destroy detritals such as apatite which are readily soluble in dilute hydrochloric acid. Clay was removed from the few clayey sandstones by boiling with .01 normal caustic soda and decanting.

Separation of the heavy minerals was then achieved by introducing 8 grams of this cleaned fraction into 150 mls. of bromoform in a 250 ml. pear-shaped separating funnel and stirring at five minute intervals over a period of 1½ hours. The heavy minerals having been collected, the bromoform was recovered by filtration under reduced pressure through a coarse sintered-glass funnel. The sand trapped in the funnel was packed down tightly and the bromoform retained in it was forced out by pouring a little water onto the sand and filtering again under reduced pressure. The water, being immiscible with the bromoform is readily removed in a small separating tube. The whole operation of the collection of the heavy detritals and recovery of the bromoform can be carried out in less than 5 minutes and 98.0 to 98.5% of the total bromoform is recovered. The method thus seems simpler, more rapid, and less costly than the standard techniques of recovery using benzene or alcohol which involve in the one case distillation and in the other distillation or loss of alcohol.

The weight of sand used in each separation was governed by 2 factors: it had to provide a minimum of about 300 grains since counts on fewer grains may be regarded as being of doubtful quantitative accuracy: more important it had to be small enough to permit almost complete separation of the heavy mineral grains so that the percentages recorded in the heavy mineral counts would represent the actual relative amounts of each mineral in the sample. It has been recorded by Ewig (1931, p. 139) that there is a tendency for some of the heavy minerals to remain caught up in the raft of lighter minerals even after several thorough stirrings. If the same percentage of each mineral was retained then the relative proportions would remain constant but it is obvious that the tendency for any grain to be retained will be influenced by its specific gravity, size, and shape and that these factors differ widely for the different species present. The lighter minerals with an irregular shape will be most seriously affected and this group unfortunately includes some of the less common detritals such as pyroxenes and amphiboles. A series of separations was therefore carried out in which exactly the same procedure was employed but the weight of sand varied from 2 to 30 gms. The heavy mineral index i.e. the percentage of heavy minerals - fig. (39) increases slightly with the weight of sand till about 5 gms. are being used, remains fairly constant for a little then decreases once more. This decrease is obviously due to incomplete separation and shows that even after 1½ hours stirring 14% of the heavy minerals remain trapped when 30 grams are used. During separation of the heavy minerals a few grains will be lost by adhering either to the funnel or to the filter paper. The fewer the total number of grains the greater will be the percentage lost in this way and it is this factor which causes of the slight drop in heavy mineral index when very small weights of sand are used. The variation in apparent percentage of each species present is indicated in fig. (39). Where 30 gms. is used the departures from the true value are + 50% for iron ores over + 30% for the heavy rod shaped grains of zircon and rutile, - 30% for platy tourmaline and - 40% for the very angular garnets. Moreover, there is a drop in percentage of the minor constituents and some, especially the light angular hornblende, may even be absent when too much sand is used. These departures become serious when more than 10 grams are used. The variations which are due to non-random splitting of the sample have been studied by comparing different varieties of the same minerals e.g. the coloured and colourless zircons. They can be seen to be very slight (fig. 39). The actual weight used was 8 gms. or 2 gms. less than the limit where variation from the true values becomes serious. Almost complete separation of every mineral is still being achieved with this weight which represents a loading of 0.2 gms/sq.cm. i.e. a layer of sand about 1 mm. or 6 grains thick.

Where the number of non-opaque heavy detrital grains separated varied between 300 and 800 the whole crop was counted. In those separations where the yield was much higher sampling by the method of quartering described by Milner (1940, p. 54) was adopted. Where a separation failed to yield at least 300 non-opaque detrital grains it was rejected.

Various techniques have been adopted for the comparison of heavy mineral assemblages. It is common practice to compare the heavy mineral assemblage of the whole sample (Smithson, 1939, p. 357). A modification of this method is to remove, by screening, the coarser constituents of the sand or gravel (Pettijohn 1939, Milner 1940) since no significant amount of heavy minerals is likely to be present in these grades. The lower limiting size of the material which can be rejected has been variously considered to lie between 500μ and 250μ. Both of these methods have been criticized for their failure to take account of variations due to sorting. The sediments of the Rhone delta, where a terrestrial augite and a marine epidote-hornblende association result from the sorting of a common parent association, provides a striking example of the type of variation which can occur where there is a marked difference in grain size of different species (Van Andel, 1955, pp. 536-538). Objections on these grounds to the method of using the entire sample are not however so serious as may at first seem apparent since the change from one association to another can be correlated with changes in the sorting and grain size and is only fairly abrupt where rapid variations in these factors takes place. Where differences in the mineral assemblage are due to differences in source then no such correlation with size and sorting is likely to exist and indeed increase in the percentage of both coarse and fine grained species can occur simultaneously. An example of this is to be found in the p-chloritoid association of the Gulf of Paria (Van Andel and Postma 1954, p. 71). In an attempt to eliminate differences due to sorting, comparisons are frequently made of the assemblage of a size-fraction common to all samples in the area. When this technique is employed for the Rhone delta sediments then the hitherto different marine and terrestrial assemblages become similar. Nevertheless the results obtained by this method never reflect the true character of the assemblage and the variation of composition with size must also be investigated because of the possibility that diagnostic minerals may be absent from the chosen size-grade. Furthermore, Rubey (1933, pp. 3-29) in a purely theoretical approach to the problem points out that one must expect significant fluctuations in the heavy mineral frequencies if one chooses to perform separations of the same size grade of sandstones of differing median grain size even although these sandstones are derived from the same source. The alternative method of comparing fractions which occupy the same position of the size-distribution curve is not valid where abrasion has been appreciable during transport for it tends to emphasise differences due to abrasion. Rubey has suggested that these two methods are supplementary and he and Russell (1936) have therefore based their comparisons on fractions obtained by combining one chosen size grade with a grade which occupies the same position of the size frequency curve. This method is not only empirical but also too time-consuming to be useful where several hundred heavy mineral concentrates have to be compared. Rittenhouse (1943) in a review of the validity of the methods in common use demonstrated that the variations across a river bed at one locality are much less for comparisons of percentages by number if the entire sample is used rather that either a selected size grade or a combination of two size grades. The present series of separations was therefore carried out on the entire sample save for that part retained on the 500 μ sieve which, it has been shown (p 100) does not contain any significant number of heavy detrital grains.

ii) Presentation of Data.

Several methods of presentation of the data have been adopted. Of these the simplest is based on the presence or absence of a mineral species. This method has been used for those species present in amounts of less than 1% of the total non-opaque detrital heavy minerals. Since only 1 or 2 grains are encountered in the whole count the possible errors of sampling and separation are too great to allow of interpretation of any variations in number percentage of the grains. It must also be recognised that presence or absence of such minerals may be due to variations in grains size and sorting of the sandstone. These differences can only be regarded as indicative of change of source when they are consistently present in an area where they cannot be accounted for by a change in current competence.

For all other species the method of comparison by number percentage has been used. This may be objected to on the grounds that fluctuation in the frequency of one mineral species will produce antipathetic fluctuations in the frequencies of other species. This can only be important where comparatively rapid fluctuations in the principal mineral species occur and within the Millstone Grit sandstones the change in the principal mineral, zircon, is gradual and can be related to the effects of selective sorting and therefore does not mask any sudden variation in the percentage of other species due to contamination from another source. The alternative method of expressing the relative frequencies of different species in terms of a 'stable' species e.g. zircon or garnet, is based on the false premiss that the amount of that 'stable' species remains constant. It is obvious that no species will in fact remain constant and therefore even validly inferred conclusions may well be false.

Rittenhouse (1943, p. 1771) having applied approximate chi-squared tests to the heavy mineral data at Bosque determined that the chances were less than 1 in 20 that the differences in mineral composition of the samples could be due to chance errors of sampling and therefore suggests that "it seems unlikely that statistical methods of comparison can be applied to number percentages of entire samples." It is here contended however that the data presented by Rittenhouse is of doubtful validity because of the method employed in the separation of the heavy minerals. It has been shown (p. 102) that complete separation of the heavy mineral crop is probably never achieved, that the percentage of the various species varies markedly with the weight of sand used, and that reliable separations are not achieved where the concentration of sand is greater than 0.2 gms/sq.cm. Rittenhouse's separations were carried out on weights of sand which varied from 0.73 gms. to 38.91 gms. and it is highly significant that in a duplicate analysis where the separations were performed on lesser weights of sand there was a tendency for a greater percentage of heavy minerals to separate. This tendency was most marked in such species as pyroxene, especially in the finer grades, and is similar to what occurred in the incomplete separations described herein (p. 102). It is therefore possible that the variations in number percentage which were found were in large part due to the separation technique. Where this technique is standardised comparisons by number percentage should be reliable. It is still recognised that variations will be dependent on 3 factors: source material, transporting medium, and conditions at the site of deposition. The second and third factors will be effective in segregating minerals of different shape, size, and specific gravity but will obviously be unable to produce any large scale variation in the ratio by number of minerals in which all three characters are very similar. Varieties of the same mineral which differ only in colour will obviously be equally affected by any sorting mechanism. If, as in the case of tourmaline and rutile, different coloured varieties typify different rock types, then a change in the relative abundance of the different varieties will indicate a change in the type of source undergoing erosion. Slight change of source rocks may not be detectable but it is unlikely that any major change should not affect the relative proportions of the different varieties of at least one of three such widely occurring species as zircon, tourmaline and rutile. It is considered that appreciable areal variation in the varieties of one or more of these minerals is a reliable guide to change of source and thus can be used to differentiate various sediment-petrographic provinces.

b) Quantitative Heavy Mineral Studies.

i) Influence of Median Size and Sorting.

Sands of different grain size were considered in order to determine the degree of dependence of the relative frequencies of the various species of heavy minerals on the median grain size of the sand in which they occur. All of the samples were taken from a small area so that all of the sands possessed the same suite of heavy detritals. Of the commoner species only zircon (fig. 40) shows a fairly close correlation between size and percentage. Here the percentage is low in the coarse sands, increases with decreasing grain size to a maximum at about 0.33 mm. and thereafter decreases again very slightly with a suggestion of a further increase when the silt grade is reached. The correlation is much poorer for tourmaline and rutile though both exhibit a maximum in the fine sand grade, a very rapid decrease in percentage in the medium sands, where the zircon percentage was highest, and another more gradual increase as the grain size continues to increase. There is no apparent connection between garnet percentage and grain size and no regression line could be sketched in.

There is practically no correlation between sorting and percentage of any mineral though there tends to be a little more rutile in the well-sorted sands. High zircon percentages occur equally frequently in both well sorted and poorly sorted sediments. It is also impossible to correlate mineral frequency with curve type although the greatest fluctuations occur in the B and F types in which the grain size parameters also vary most widely: the mean zircon percentage for the M sands of Stirlingshire is 75.0; the corresponding value for the MC types is 73.8. The value of $P > 0.9$ indicates that there is no possibility that this slight difference is significant.

Since for a given area there is so little relation between size and sorting and mineral frequency it follows that a marked change in the frequency of any detrital species in any area is likely to be due to a change of source. If in the same area there is a change in other species, especially species of different habit or different specific gravity, then it is fairly certain that that area constitutes a true sediment-petrographical province. This, according to Edelman (1933) should form a unity as regards age, distribution, and provenance. The results of the 304 separations carried out in this investigation are contained in Appendix III.

ii) <u>Areal Variation of Detrital Species</u>.

As with the grain size distribution it proved impossible to confine the areal study of the heavy mineral variation to any particular horizon of very limited vertical extent. Two separate ranges from Castlecary horizon to No. 2 Marine Band and above No. 5 Marine Band i.e. the massive sandstones at the top of the Millstone Grit were therefore used for this study.

<u>Lower Group</u>

The variation in each of the commonly occurring detrital species has been considered separately. Throughout Clackmannan and along the western outcrop of the Millstone Grit of the Central Basin the <u>Zircon</u> percentage (fig. 41) is over 70 and commonly over 75. Between Cumbernauld and Glenboig however, the percentage drops to about 60 while in the Glasgow area there is an even sharper fall to 40%. Along the eastern outcrop the zircon percentage is about 65 falling off southwards to Levenseat where values of less than 50 are common. In the Midlothian Basin the mean value is about 65 but again there are values well under 50 along the eastern margin of the syncline and especially at Port Seton.

When the different varieties of zircon are considered it is found in the Central Basin there is a gradual southwards increase in the malacon/zircon ratio (fig. 42) with a slight maximum in the east of

Clackmannan, some high values in the Glasgow and Cumbernauld districts and a much more sharply defined high at Levenseat where malacons commonly constitute 15% of the total zircons. In the Midlothian-Fife Basin there is again a southwards increase but the mean value is under 5% while in the Central Basin it was over 8%.

<u>Malacon</u> forms by the alteration of zircon and therefore, since most active alteration is likely to take place during erosion and transport, the malacon percentage should increase in the direction of transport. The southward increase in both basins would seem to indicate, as did the sedimentary structures, that most of the sands are being derived from the north. The lower values in the Midlothian -Fife Basin may indicate shorter or probably more rapid transport of the material deposited there. Such high values as are found at Levenseat on the south-east margin of the Central Basin are most likely to occur in an area of second-cycle sands.

The possibility of introduction of material from another source into this area is enhanced by an increase in the Purple Zircon/ Colourless Zircon (fig. 43) ratio which is fairly constant over the remainder of the Central Basin. A slightly higher percentage (10%) of purple zircon is present in some of the Fife and a few of the Mid-lothian concentrates.

Over much of the Central Basin and in Fife red and yellow <u>rutile</u> (fig. 45) together constitute about 10% of the heavy detritals, while in Midlothian the average is 13%. In 3 areas of the Central Basin there are marked departures from the normal frequency. In the east of Clackmannan there is a distinct minimum with values of less than 5%; at Levenseat the percentage rises sharply to 20 while in the Glasgow and Cumbernauld districts there is an even more distinct maximum with over 50% of rutile in a few concentrates.

Distribution of the purple brown variety is more restricted (fig. 46). It is a major constituent only in east Clackmannan with an area of decreasing values extending westwards into Stirling. A little of this variety is also commonly present in Fife but elsewhere in both Central and Midlothian Basins it is entirely absent. The very distinct maximum in purple brown rutile in Clackmannan shows up even more clearly when the Purple Brown Rutile/Rutile ratio is considered (fig.47).

There is a gradual southwards increase in tourmaline (fig. 44) in the Central Basin with a mean value of about 7%. Much lower values $< 3\%$ are found in the Glasgow area and also in Midlothian where a few concentrates are lacking in this species. Very high percentages, in some cases over 30% occur in the Levenseat area. The relative proportions of brown, green, and blue varieties are also very variable. Over most of the Central Basin they are present in the ratio 4: 2: 1. The blue variety is absent from east Clackmannan and from the Glasgow area. In this latter district there is also a very considerable increase in brown tourmaline some of which contains carbonaceous inclusions, and the ratio becomes 10: 1: 0. The green variety is almost as abundant as the brown at Levenseat, 5: 4: 1, but is scarce in Clackmannan, 3: 1: 0. Brown is the dominant variety in Fife, 8: 2: 1, but in Midlothian the green variety is almost as common 5: 4: 1 and indeed is the most abundant variety in some of the garnetiferous sands.

Garnet (fig. 48) is absent or forms less than 1% of the heavy detritals throughout most of the Central Basin and in Fife. More richly garnetiferous sands occur at Glasgow, Levenseat, and in parts of Midlothian and in N.E. Clackmannan.

The same antipathetic relationship between monazite and sphene which Mackie has shown to exist in the Highland Granites is found in the Millstone Grit sands. Sphene is distributed spasmodically throughout the Central Basin but is not present in the Glasgow area or at Levenseat and is very rarely found in the Midlothian-Fife Basin. In each of these areas the concentration of monazite is commonly over 3% (fig. 49). Elsewhere the percentage of monazite is below 1 and frequently 0.

Apatite is a very uncommon mineral in the Millstone Grit sands and the few concentrates containing more than 1% of the mineral occur around Glasgow, Levenseat and less commonly along the eastern margin of the Midlothian Basin.

Epidote is virtually absent from the Midlothian-Fife Basin and is only occasionally present in small quantity in the Central Basin. In the Glasgow district however large colourless epidotes may form as much as 5% of the heavy detritals.

Fluorite is commonly present only at Levenseat and Staurolite is confined to the Glasgow area, and the eastern margin of the Midlothian Basin.

These variations reveal the existence of 6 heavy mineral associations whose distributions are given in fig. (50). The assemblages characterising them are represented in Table 7. The Central C-Zircon assemblage consisting of zircon with lesser amounts of tourmaline and rutile, covers the greater part of the Central Basin. In Clackmannan it is replaced by the K (= Clackmannan) rutile assemblage which is very similar save that it is much richer in the purple-brown variety of rutile and contains rather more sphene. The G (= Glasgow) rutile assemblage occupies the western part of the basin and is mixed with the C-zircon assemblage between Glenboig and Cumbernauld. It contains about equal amounts of zircon and rutile with lesser amounts of garnet, epidote, and monazite. The south-east of the basin is occupied by the L - tourmaline assemblage (L = Levenseat) which contains abundant zircon, tourmaline, and rutile with lesser amounts of garnet and fluorite. The F (= Fife) zircon assemblage is almost identical with the C-zircon assemblage but contains much more monazite, more brown tourmaline, and almost no blue tourmaline. The Midlothian M-garnet assemblage is found only on the extreme eastern margin of the Midlothian-Fife Basin at Port Seton and Leven. Garnet is the most abundant mineral and there are lesser percentages of rutile, zircon, and monazite. Over the rest of the Midlothian Basin a little of this assemblage may be mixed with the F-zircon association.

It was concluded from comparison of the mineral content of sands of different grain-size that sorting has had little effect. Consideration of the above associations supports this conclusion.

The K-rutile assemblage could not be derived from the C-zircon assemblage since the two differ principally in the proportions of the different varieties of rutile which, being of the same size, shape, and specific gravity, would all be equally affected by any sorting mechanism. Sorting is also likely to produce the greatest relative changes in the percentages of very dissimilar species and only small changes in like species. The G-rutile assemblage differs very greatly from the C-zircon assemblage in the relative frequency of two minerals of similar shape and specific gravity, zircon and rutile. Moreover rutile and tourmaline showed similar regression lines with respect to grain size and therefore one would expect that any increase in the proportion of rutile in a concentrate would, if due to size sorting, be accompanied by a corresponding increase in tourmaline. At Glasgow the rutile percentage is greatly increased, the tourmaline percentage halved. From these results from the greatly changed varietal ratio of tourmaline and from the appearance of staurolite and epidote it would appear that the G-rutile assemblages forms a true sediment-petrographical province. The L-tourmaline association shows a marked increase in tourmaline and a smaller increase in rutile at the expense of zircon when compared with the C-zircon assemblage. This is exactly what would be expected to occur by progressive sorting. Much of the L-tourmaline assemblage is therefore probably derived by differentiation of the C-zircon association, but the appearance of garnet, fluorite and a very occasional grain of staurolite suggest that at least a little material is being derived from some other source: so does the increase in the relative proportion of the green variety of tourmaline.

The F-zircon assemblage of the Midlothian-Fife Basin is very similar to the C-zircon assemblage but contains a much greater percentage of monazite. Both zircon assemblages were probably derived from a similar source, the granites of the F-zircon sources being the more acid. In the F-zircon assemblage the brown variety of tourmaline is most abundant, in the M-garnet association the green variety is almost as important; tourmaline and zircon decrease while rutile increases. These, coupled with the sudden abundance of garnet suggest that the two assemblages are derived from different sources.

The average size of 4 of the diagnostic minerals of the various associations is shown in Table 8. These values were based on the measurement of grains in one concentrate from each assemblage, each concentrate being derived from a sample of the same median grain size. The largest zircon and rutile is present in the G-rutile and M-garnet assemblages. The garnet of the G-rutile and L-tourmaline associations is coarser than elsewhere in the Central Basin. Notably larger epidotes are also found in the G-rutile association.

From a study of several concentrates in the C-zircon association it was found that little or no relation exists between the mean size of the heavy detritals and the mean size of the sediment. There is equally little connection between the sorting of a 'heavy' species and the sorting of the sand in which they are found. This may best be demonstrated by comparison of the grain size distribution of the sand

and of the zircons it contains (fig. 51). This observation is in accordance with the results of previous studies (Van Andel 1950) and it is suggested (Van Andel and Postma 1954) that it results from the current sorting being insufficiently sensitive to affect the narrow size range of the heavy detritals. The grain size distribution of a heavy species is therefore mainly a function of the source material and the differences in mean size contained in Table (8) are an additional proof that the various associations are derived from different sources.

Upper Group

In the top sandstones of the Millstone Grit of the Central Basin zircon (fig. 52) forms 75% of the heavy detritals of Clackmannan and slightly less further south. Percentages under 50 are to be found west of Lanark, where no deposition occurred during formation of the lower group, and in parts of the Midlothian-Fife Basin. As before there is a gradual southwards increase in the Malacon/zircon ratio and a lower proportion of malacon in the Midlothian Basin. No high percentages are now observed at Levenseat. The purple zircon/zircon ratio remains fairly constant, the mean being slightly higher for the Midlothian than for the Central Basin. Over much of the Central and Midlothian Basins the percentage of rutile (fig. 54) has remained about 10% and there is still an area of values $<$ 4% in Clackmannan and higher values on the eastern margin of the Midlothian Basin. The maxima at Glasgow and Levenseat have disappeared. The purple brown variety (figs. 56 and 55) again forms over 5% of the Clackmannan concentrates and is absent elsewhere save for an area west of Lanark where about 2% is present. There is also very little of this variety in Fife.

The southward increase in tourmaline in the Central Basin persists (fig. 53) the percentage rising from 5 in Clackmannan to 10 in the south of the basin. The mean value in Midlothian is lower at 3%. Over most of the Central Basin the ratio of brown, green and blue varieties is 4: 2: 1. The blue variety is absent from east Clackmannan (3: 1: 0) and is scarce in the extreme west (6: 3: 1). The brown variety is dominant in Fife (8: 2: 1) while in Midlothian the ratio is similar to that of the Central Basin.

In only 2 areas is the percentage of garnet over 1, (fig. 57) west of Lanark where it may be over 30% and in Midlothian where over 40% is found at Port Seton and Joppa with smaller values further south. There is now an even more marked contrast in the monazite content of the sands of the Midlothian-Fife basin with an average of 5% and those of the Central Basin where the mineral is often absent and values in excess of 1% are uncommon (fig. 58). A little apatite is still present at Glasgow and rarely in Midlothian. Over 3% of epidote is present in some concentrates from the Glasgow area: elsewhere it never forms more than 1% of the heavy detritals.

The extent of each of the sediment-petrographic provinces, as indicated in fig. 59, differs somewhat from those of the Lower Millstone Grit. The C-zircon assemblage now covers all of the Central

Basin with the sole exception of a small area in the eastern part of Clackmannan where the K-rutile assemblage persists. In the Glasgow area the rather high percentages of rutile and epidote indicate an admixture of the C-zircon and G-rutile assemblages. With the submergence of the positive area to the south of the Central Basin the L-tourmaline province has disappeared but west of Lanark another assemblage, the H (= Hamilton) garnet assemblage appears. It contains abundant zircon and garnet together with a little tourmaline and rutile (red and purple brown varieties). Within the H-garnet area are channels of current bedded sands, such as those at Stonehouse Viaduct, which carry a C-zircon assemblage. A few samples from the eastern margin of the Midlothian Basin carry an M-garnet assemblage while at Joppa on the west of the basin is a small fringe of similar garnetiferous sands of the J-garnet association. The remainder of the Midlothian-Fife Basin is occupied by F-zircon sands. Derivation of the various assemblages is discussed in Chapter VII.

iii) Vertical Variation in Heavy Mineral Assemblage.

The vertical variation in the heavy mineral assemblage of the Millstone Grit sandstones has been observed at the 7 localities indicated in fig. 60. Of these, only one, the Bogside No. 4 Bore, is a true vertical section. The others are compiled from a series of samples collected across the strike. In these latter, determination of the exact position of any sample in the vertical succession is not absolutely accurate, particularly in the upper part of the Series where marker horizons are so few. The horizon has here been derived from the position of the station and the dip of the beds, but is still sufficiently accurate to show where any mineralogical changes occur. The vertical variation in the percentage of each of the 4 most abundant minerals - zircon, tourmaline, rutile, and garnet, is indicated in figs. (61 and 62).

The most striking feature of these vertical successions is the sudden eclipse of garnet, often the most abundant mineral of the Upper Limestone Group, close above the Castlecary Limestone. Apatite and staurolite (not represented) also become very rare above this horizon while the zircon percentage is greatly increased. This sudden change in the heavy mineral assemblage may be due to one of three causes. The garnet, apatite, and staurolite, all of which occur as fairly large grains, may have disappeared as a result of decreased competence of the transporting medium: they may have been destroyed by intra-stratal solution or by weathering and transport under physically or chemically unfavourable conditions: their absence may result from a change in the location of the major source area.

It has already been shown that the garnet percentage is not dependent on grain-size or sorting. If the minerals had been lost as a result of intra-stratal solution then it seems probable that they would also have been removed from the lithologically similar Upper Limestone Group. An abundance of garnet, apatite, and staurolite would also be expected in sandstones overlain by or included within thick impermeable beds yet they are absent below the thick fireclay seams. There remains the possibility that the garnet was destroyed as a result of different conditions of weathering and transport. In this case it is unlikely that garnet rich concentrates would be found anywhere in the basins of deposition yet some areally restricted associations e.g. M-garnet associations are composed largely of that mineral. Moreover if some minerals are removed by solution then the percentage of the more stable minerals should increase. Since the percentage of material to be removed is known the percentile increase in the other species is readily calculated. Comparing the C-zircon assemblage with the Upper Limestone Group assemblage it is found that there is a much greater increase in the zircon percentage than would be expected while the percentage of tourmaline and rutile, which are almost as stable, remain unaltered. It is therefore unlikely that the garnet could have been removed by solution particularly since such unstable species as the amphiboles and pyroxenes are often minor constituents of the C-zircon assemblage. It therefore seems that there was a change in the source area probably consequent on the earth movements which are known to have occurred immediately prior to the deposition of the Millstone Grit sediments. The disappearance of garnet in the Fell Sandstone of the North of England was also attributed to a change of source (Robson 1956). The reappearance of garnetiferous sands at the top of the Millstone Grit and in the overlying Coal Measures indicates either renewed supply from the Upper Limestone Group source areas or less probably, since the onset is fairly abrupt, sufficient erosion of the Millstone Grit source to expose the garnet zone.

While the Millstone Grit sands are typically lacking in garnet, slightly garnetiferous sands can be seen to be present at several horizons nearly all of which are coincident with or immediately below a marine band. The most persistent garnetiferous horizons occur about the position of No. 0 Marine Band and also with Nos. 3 and 6 Marine Band Group. Even at these horizons garnet is present only in the north-east part of the Central Basin and it is therefore from this direction that the garnet sands are introduced. Since there is a return to the normal non-garnetiferous assemblage above each of these marine horizons it would seem that the appearance of garnet is due to a change in the drainage pattern within the basin of sedimentation rather than to any change in the source area. It has been postulated (p. 98) that the basin was almost completely silted up prior to and during deposition of the marine horizons, the greater part of the debris carried in by the main distributaries being confined within certain well-defined channels roughly coincident with the axis of the present syncline. Material introduced by minor distributaries or by the erosion of garnetiferous Carboniferous Limestone sediments along the eastern margin of the Central Basin would therefore constitute a much greater part of the total sediment of that eastern part of the syncline than at other times, thus altering the character of the assemblage. If all of the garnet is introduced from the east or north-east it cannot be present on the west side of the main distributary channels. There is therefore little or no garnet at any horizon in the Glenboig and Cumbernauld districts on the west side of the syncline.

Another common feature best seen in the Bogside No. 4 section is the sudden increase in tourmaline percentage immediately below or in the lower part of all marine bands except Nos. 1 and 2 where there are slight rutile maxima similar to the rutile maxima occurring immediately below the tourmaline maxima of the other groups. These maxima almost certainly result from the decrease in current velocity as the basin silted up prior to the formation of the marine band. The tendency for rutile and tourmaline to increase in the finer grades has been demonstrated (fig.40). The tourmaline maxima below the Lower and Upper Fireclays of the Glenboig and Cumbernauld districts also result from decreased current competence.

The interdigitation and intermingling of sands of 2 assemblages is apparent in the 3 westerly sections. In that part of the Cumbernauld succession below the Lower Fireclay, are found the high rutile values and comparatively low zircon values resulting from the admixture of G-rutile and C-zircon sands. Higher in the succession the sands carry a C-zircon assemblage with a possible return to the G-rutile type at the very top of the Millstone Grit. Six miles to the north north-east at Torwood, sands of C-zircon type occupy almost the whole of the succession. Between Nos. 1 and 2 Marine Bands however there is a marked increase in the rutile percentage indicating that at this time the influence of the G-rutile association reached its furthest north-easterly extent. At Glenboig 6 miles south south-west of Cumbernauld the basal sands again carry a C-zircon assemblage.

The rutile percentage only begins to increase just below No. 2 Marine Band and persists to the Lower Fireclay horizon so that in this area the mixture of G-rutile and C-zircon sands begins slightly later than at Torwood but lasts longer. In the Glasgow area G-rutile sands occupy the lower part of the series, the highest rutile values occurring above No. 2 Marine Band. Above No. 3 Marine Band there is some decrease in the amount of rutile and the sands carry a mixed C-zircon G-rutile assemblage. The sediments of this western part of the Central Basin are therefore being swept in and deposited ahead of 2 advancing delta complexes; one carrying the G-rutile assemblage and advancing from the north-west, the other with the C-zircon assemblage advancing from the north. In the lower part of the Series the relative importance of the G-rutile sediments increases and they are spread over an ever increasing area so that at the No. 2 Marine Band horizon they affect the composition of the heavy mineral assemblage over all of the western part of the Central Basin. Toward the No. 3 Marine Band Group and thereafter throughout the remainder of the Millstone Grit period the proportion of material carried in from the north becomes greater, the G-rutile sediments are diverted westwards and the C-zircon assemblage spreads as far west as Glasgow.

At Levenseat most of the succession is again occupied by C-zircon sands but the slightly garnetiferous L-tourmaline association is present at the base of the Millstone Grit, above No. 2 Marine Band, a little below the Ginstone and again possibly at the top of the succession. Since the L-tourmaline association is considered to be derived from the erosion of Upper Limestone Group sediments to the south it follows that uplift occurred in that area at each horizon where the L-tourmaline association appears, the greatest uplifts, accompanied by the coarsest ill-sorted sandstones, being those at the base of the Millstone Grit and below the Ginstone.

From the few observations in the Midlothian Basin it would appear that M-garnet sands are present only at the base and top of the succession. Between these horizons the F-zircon assemblage occupies the whole basin.

PROVENANCE OF THE MILLSTONE GRIT SEDIMENTS

The information regarding source rocks afforded by each mineral species is considered here and correlated with the areal and vertical variations and mineral associations discussed in the last chapter to build up a composite picture of the source area.

a) Varietal Mineral Characteristics.

Quartz

As the principal detrital constituent of almost all sandstones quartz is more likely to afford a reliable guide to the nature of the source area as a whole than any of the lesser constituents. Unfortunately it occurs in many types of igneous and metamorphic rocks and great attention has therefore been paid to the particular characters of the mineral to determine whether these vary in different rocks.

Mackie (1896) divided inclusions in quartz grains into 4 groups - Regular, acicular, irregular, and negative - and states "....... acicular and irregular inclusions pre-eminently abound in the quartz of granites. That the regular group is to be found in various proportions, but always in relatively large numbers in the quartz of gneiss and the younger schistose rocks." The results of the investigations of Tyler (1936) suggest that this precept may not be of universal validity while Krynine (1940) makes the contrary statement that "The inclusions in metamorphic quartz are usually much more acicular in character." Furthermore Harker (1932, p. 231) describing the Dalradian schistose grits and quartzites points out that "regularly oriented trains of secondary fluid pores" are developed. Mackie had considered such trains as indicative of an igneous source and they are in fact occasionally present in the quartz of pegmatites. The latest study, on a more statistical basis, by Keller and Littlefield (1950) indicated that "..... igneous quartz is relatively free from large regular inclusions but that the quartz of schist more likely contains them. Acicular inclusions are somewhat more abundant in igneous rock quartz. Globular inclusions are definitely more abundant in igneous quartz than in schist "(No mention is made of the globular inclusions of quartzites for indeed none were examined)" ... irregular inclusions are more abundant in igneous rock quartz than in either gneiss or schist."

From the assessment of these various accounts it would appear that,

1) The presence of numerous regular inclusions is indicative of a metamorphic source
2) No very reliable conclusions can be based on acicular inclusions
3) Globular inclusions indicate an igneous or an arenaceous metamorphic source. Where the globules are arranged in parallel trains they must have formed in quartz subject to a unidirectional stress and hence such inclusions denote a quartzitic source. Where the globules are isolate or are arranged in randomly oriented streams it is more probable that the quartz is derived from a plutonic igneous source.
4) No conclusions can be based on irregular inclusions unless these

are abundant in which case the quartz is of igneous derivation

The results of a study of 65 randomly distributed Millstone Grit sandstones are shown in Table (9a) while data for 5 Upper Limestone Group sandstones is presented for comparison in Table (9b). The dominance of parallel trains of globules and the frequency of occurrence of regular inclusions indicate that the source rocks largely consisted of metamorphic species among which grits, quartzites, and gneiss were abundant. The presence of numerous randomly distributed globules together with acicular and irregular inclusions would seem to denote the presence of smaller areas of acid igneous rocks. The Upper Limestone Group has very similar inclusions save that rather less of the globules are in parallel arrangement. This same tendency is present in the few highly garnetiferous Millstone Grit sandstones, and presumably reflects a slightly smaller percentage of quartzitic source rocks.

The character of the extinction has also been used as a criterion of paragenesis. It is known that quartz when subjected to pressure develops strain shadows or undulose extinction. However undulose extinction is not present in all grains of metamorphic origin, nor is it confined to such grains since fragments of igneous quartz quite often display strain shadows. Further it has been shown (Fig. 2) that more straining is observed in large than in small grains, this phenomenon being considered to reflect not a difference in source of the different grain sizes, but rather the greater stress to which the larger grains must be subjected and the greater difficulty of observing strain in small grains. Nevertheless, while the percentage of quartz of metamorphic origin cannot be computed from the percentage of grains with undulose extinction, it is permissible to infer a largely metamorphic source where this percentage is high and an igneous source where it is low. Since on an average 7 grains of every ten are strained it would appear that there is a greater contribution of detrital material from metamorphic than from igneous sources.

Yet a third method of determining the origin of the quartz has been proposed by Bokman (1953) who makes use of the fact that unidirectional stress tends to produce crystals of relatively elongate habit. He has therefore determined the ratio of the long axis to the intermediate axis for granites and schists and has shown that the grains are significantly more elongate in the latter. Moreover it has been demonstrated (Pettijohn 1949, p. 54) that "except for slight shape modification produced by abrasion the end shape of a sand grain or pebble appears to be determined by its original shape." The elongation distribution of sand grains will therefore indicate the source rock of that sand except where significant changes in that distribution have been affected by the transporting medium or by diagenesis.

The first obvious result of transport is abrasion which, being more active at the ends of grains, will produce a slight decrease in mean elongation. Long grains will be affected more than short and large grains more than small. Some idea of the changes wrought by abrasion can therefore be inferred from the comparison of adjacent coarse and fine sands. Where both show very similar elongation patterns as do the Millstone Grit sands the effects of abrasion have been negligible. The mean elongation of the coarse sands is 1.60 $\pm$ 0.08 and of the fine 1.63 $\pm$ 0.05.

Secondly, the sorting action of the transporting medium tends to segregate grains of different size and therefore if there is a marked change in elongation with size at source then the mean elongation of a particular sand will vary according to its mean size. Such differences can also be detected by a comparison of different grades of sand: and therefore they too are unimportant. Very different patterns may also be produced where shape sorting has been appreciable. The relative velocities of differently shaped grains is dependent on the surface area/volume ratio so that where the volume is constant the velocity will increase with increasing surface area. Hence there is a tendency for lath-shaped and rod-like grains to outrun equants (Allen 1945). The mean elongation of the constituent grains of a sand unit will therefore increase somewhat away from source except where abrasion effects outweigh those of shape sorting.

In two isochronous sands of the same median grain size, the second being 20 miles further from source (as revealed by current-bedding directions) than the first, the mean elongation has increased from 1.63 $\pm$ 0.05 to 1.71 $\pm$ 0.04 i.e. the only changes in distribution have been a nonsignificant increase in elongation and a decrease in standard deviation from 0.49 to 0.43 which doubtless reflects the improved sorting resulting from more prolonged transport. The elongation characteristics of several sandstones were determined by the measurement of 200 loose grains scattered on a glass slide. Comparative measurements of thin sections cut parallel to the bedding planes of the sandstone produce more widely spread distributions in which the mean is .04 to .10 lower. The differences are a consequence of the departure from the horizontal of the long axis of the quartz grains so that a section cut in that plane does not traverse the maximum length of the grain. Table (10) shows the elongation parameters of 5 Millstone Grit sandstones a granite, a schist, and a Dalradian schistose grit. The close affinity of the sandstone parameters with these last two indicate the predominance of metamorphic rock types in the source area of the Millstone Grit sediments.

Since the sedimentary structures and thickness variations show that the source lay somewhere at no great distance to the north, a considerable number of samples of the Highland metamorphic rocks were examined in order to determine which of them contain quartz similar in character to that of the Millstone Grit. The first investigation was designed to determine the changes occurring in quartz grains as a result of progressive metamorphism. Some 215 sections in a traverse across the metamorphic zones in the altered grits of Kincardineshire were examined for this purpose. In the normal grits, those with an originally argillaceous matrix, quartz of suitable size is present in the low zones but with increasing grade of metamorphism rapid comminution of the larger grains ensues so that by the time the middle of the biotite zone is reached hardly any quartz of sand size remains. This condition persists through the garnet zone and much of the staurolite zone but thereafter recrystallisation produces increasingly large quartz grains. There is however a marked difference in the inclusions of this high-grade recrystallised quartz for, whereas in the low grades parallel trains of globules had predominated with but a few regular inclusions of zircon, the inclusions are now almost exclusively of regular laths of mica together with occasional blebs of quartz. Since in the Millstone Grit sandstones globular inclusions are most common and regular mica tablets comparatively rare, it would appear that the quartz was largely derived from low-grade metamorphic rocks.

The one exception to this behaviour of quartz during metamorphism is to be found in the pure quartose bands where recrystallisation rapidly produces a quartzite whose grain size increases with the grade of metamorphism. In them the inclusions are of zircon, tourmaline, and mica. Trains of fluid inclusions do not seem to persist to the highest zones.

In order to determine whether similar conditions exist at the same grade throughout the Highlands some 60 suitable Dalradian and Moine rocks and 2 specimens of Lewisian Gneiss were examined. Of the schists 1 in 3 from the chlorite and chloritoid zones carry the right type of quartz; only 1 in 4 from the biotite zone had large enough grains and in that, mica inclusions were rather too numerous; regular inclusions of mica and zircon and blebs of quartz characterise all the higher zones, so that although 3 of 7 garnet schists, 2 of 4 staurolite schists, 4 of 6 kyanite schists, and 2 of 3 sillimanite schists did have quartz of the right size none could have been more than a minor contributor. Quartz schists do contain suitable grains together with fragments more finely polygranular than any commonly found in the Millstone Grit. All 12 of the gneisses examined, including 2 Lewisian Gneisses, had big enough quartz grains but all, save one Lewisian specimen had abundant mica inclusions, the Lewisian and 2 others had numerous blebs of quartz and feldspar included in the larger grains, 4 were too finely polygranular, 2 were crowded with irregular inclusions, while only one had more than a very few trains of liquid inclusions so that no one nor any combination of them could constitute more than a very small part of the regimen of the Millstone Grit rivers. The Moine granulites also have few globular trains and rather too many mica inclusions. A more suitable quartz source is to be found in the Dalradian quartzites some 8 of which were examined. Only 2 of those however have considerable development of liquid inclusions, while mica inclusions become too abundant wherever a high grade of metamorphism has been attained. Most probable source rocks of all are the schistose grits which occur all along the Highland Boundary Fault: 9 of 10 have quartz similar in size, shape, and inclusions with that of the Millstone Grit. Every type of straining, including the 'multiple twin' effect, and every kind of polygranular fragment to be found in the sandstones has its counterpart in the low-grade schistose grits of the Ben Ledi Group. (Plate 10).

Feldspar

The only feldspar considered likely to give any indication of provenance was the homogeneous alkali feldspar. A similar type possessed of 2 cleavages at 68° and having a very high optic angle has been observed in parts of the Ben Ledi Grits, Central Perthshire Quartzite, and Appin Quartzite.

Rock Fragments

The only commonly occurring rock fragments are of a quartzite containing no feldspar other than a little microcline. Less common fragments of schistose grit confirm the above conclusions while schist and chert fragments indicate that these types were also present in the source area.

Heavy Minerals

Zircon

Zircon is one of the most ubiquitous of all accessory minerals so that the presence and even the abundance of zircon in a sediment cannot by itself indicate the provenance of that sediment. Great attention has therefore been paid to the study of varietal characteristics to determine whether these vary in different rock types (Tyler and Marsden 1937, Tyler 1940, Poldervaart 1950, 1956, Slaviic 1952, 1953).

Within other groups where zircons are euhedral or ovate, distinction can be made on the basis of elongation. Table (11) summarises the results of several such studies while the typical elongation frequency distributions of zircon in granitic and metamorphic rocks are illustrated in fig. (63). Quartzites and schists contain rounded, abraded, 'sedimentary type' zircons because there has been no metamorphic recrystallisation of the highly refractory zircon of the sediments from which these rocks formed (Harker 1932, p. 12). The mean elongation of zircon is 1.4 - 1.6 for schists, 1.5 - 1.7 for quartzites. Similar low elongations are to be found in many gneisses, but, where the grade of metamorphism becomes very high the zircons do begin to recrystallise and assume a more granitic habit. The elongation ranges from 1.7 to 2.2 with a mean of about 2.0. In granites the length-breadth ratio is even more variable and while it is generally about 2.5 it may be as low as 2.0 or it may, in a few cases, be over 3.0. The cause of the variation is rather obscure but elongate zircons seem most common in the alkaline or more basic types. Pegmatites tend to contain the most elongate zircons of all; the mean elongation is rarely less than 3.0.

Zircon elongation studies on the Monadhliath granite and the surrounding Moines were carried out by Wyatt (1954). The values he obtained agree fairly closely with those of other workers. In order of increasing elongation they are; Quartzite 1.6, Moine Granulite 1.7, Moine Gneiss 1.9 and 2.0, granite 2.2, aplite 2.4, granodiorite 2.4, granite contaminated with country rock 2.2 and 2.8 (fig. 64). The occurrence of significant proportions of zircon with elongations in excess of 4.0 is restricted to pegmatites and a very few granites including some of the foliated granites of the Scottish Highlands (Mackie 1932, p. 26).

To augment these observations 3 Dalradian horizons have been sampled, the Central Highland quartzite, Ben Lui Garnetiferous Mica-Schists, and Ben Ledi Grits. Their elongation distributions have mean values of 1.6, 1.5 and 1.8 respectively.

Grains derived from any of these sources have rather lower elongations than the zircon of the parent rock because of abrasion during transport. Since the grains are small however, the effects of abrasion are slight except where reworking has been very extensive as in a beach sand. Moreover it has been shown (fig. 51) that zircon size and sorting are independent of the median grain size and sorting of the sediment. Changes in zircon elongation between the various assemblages are therefore to be attributed to changes of rock type at source. The inability of the current velocity to affect the zircon elongation is demonstrated in broken line curves (fig. 63). These indicate the zircon elongations of a very coarse and medium-grained sandstone occurring 4 feet apart in the upper part of Bogside No. 4 Bore. Their elongation distributions are nearly identical.

The zircon elongation of each association was determined from 2 samples taken as close as possible to the supposed position of influx of that assemblage in order to minimise the effects of abrasion and of mixing with the zircon of another association.

The zircons of the K-rutile association (fig. 63) are quite remarkably elongate. The mean elongation is 2.5, 20% have elongations over 3.0 and there are comparatively few below 1.5: such zircons must be derived almost entirely from acid igneous rocks among which pegmatites, basic granites and possibly foliated granites predominate. The mean elongation of the C-zircon assemblage which occupies most of the Central Basin is slightly lower at 2.2, only 8% have elongations of over 3.0 and there are many more grains with elongations of about 1.5 (fig. 65). Nonetheless a largely igneous origin is again probable the main source being granite and pegmatite with possibly some granite gneiss. The increased number of grains with an elongation of about 1.5 indicates that some zircon is also being supplied from quartzite or schist. In both of these assemblages the zircon shape index, that is, the percentage of euhedral zircon, is over 7 which is unusually high for any rock type except granite or pegmatite. Towards the base of the Millstone Grit in the Central Basin there are several garnetiferous sands. In them the zircon shape index is low and the mean elongation is 1.8 with the mode at 1.7 (fig. 63). None of the zircons have elongations of over 3. It therefore follows that these sands do not represent merely an extension of the drainage area to include some garnet schists. Where the sands are garnetiferous the whole regimen of the inflowing rivers has changed. In one area occupied by the C-zircon assemblage the zircon shape index is < 1 and the elongation falls below 2.0. This is at Linlithgow where the grain size distribution indicated an area of beach sands. The rounding and consequently lowered elongation are due to reworking by wave action.

The G-rutile association exhibits a very different zircon elongation distribution which is bimodal, the modes occurring at 1.5 and 2.1 (fig. 65). None of the zircons have elongations in excess of 3.0. The shape index is again < 1. It would therefore appear that the zircon of this assemblage was being derived partly from schist or quartzite and partly from granite. The absence of very elongate or euhedral zircons suggests that the granite was acid and that pegmatites were rare in the source area.

The elongation distribution (fig. 65) of the F-zircon assemblage is very similar to that of the C-zircon assemblage and suggests a similar largely granite origin.

Two modes are present in the M-garnet association (fig. 65) a large primary mode between 1.5 and 1.7 and a smaller secondary mode at 2.5. Only the more elongate zircons are ever euhedral. Derivation is again from an area of quartzite and schist with smaller contributions from granites, probably acid granites on account of the absence of very elongate zircons.

In both the L-tourmaline and H-garnet associations to the south of the Central Basin zircon with a mean elongation of between 2.0 and 3.0 occurs together with well rounded, almost equant zircons. The latter are much less common, the shape index is high, 4.8 - 6.6, and it is suggested that these assemblages are in fact mixtures of the C-zircon assemblage with material from another source which from the shape of its zircons is either metamorphic or, more probably because of the position of these assemblages, sedimentary, the sediments beingof metamorphic derivation.

Mackie (1932, p. 25) suggests that a broad distinction may be made between acid and other granites on the basis of zoning. Acid granite zircons are commonly closely zoned and often have dark cores while limpid, unzoned zircons are found in other types. In every association in the Millstone Grit unzoned types predominate. Some zoned zircons are present in the G-rutile, and F-zircon assemblages. These are also the assemblages richest in monazite and probably the only ones to which acid granites make any significant contribution.

Tourmaline

Most of the tourmaline grains of the Millstone Grit sands belong to types 1 and 3a of Krynine's classification (Krynine, 1946). They are therefore of granitic or quartzitic origin. Well-rounded grains of a reworked type and a blue pegmatitic variety (Krynine's type 2) are also common. In the Glasgow area there are a few brown grains crowded with carbonaceous inclusions (type 3b) which should be derived from slates, phyllites, or non-quartzose schists. Elsewhere this type is very rare even in the most garnetiferous concentrates.

Information on the tourmaline of the granitic rocks of the Scottish Highlands is afforded by Mackie (1932, p. 32) who found it in only 6% of the Newer Granites. Brown and green idiomorphic prisms occur in 40% of the Foliated Older Granites. Blue and brown varieties are present in 20% of the pegmatite veins. There are few descriptions of the tourmaline of the Dalradian and Moine Series. The brown and green varieties are rarely listed as accessory minerals in the Memoirs of the Geological Survey - Sheets 54, 55, 65 - and seem most common among the quartzites. Barrow (1893, p. 342) found that the mineral occurred in very small amounts in the Dalradian metamorphics of north-east Forfarshire. The olive-green variety was present in the garnet-schists and a blue variety in the limestones and staurolite schists. Mackenzie (1956, pp. 35, 101, 105) records the occurrence of olive-green tourmaline and lesser amounts of red-brown tourmaline in the Moine gneiss of Upper Strathspey.

In most of the Millstone Grit sediments the brown, green and blue varieties are present in the proportions 4: 2: 1 though in the highly garnetiferous concentrates the green variety predominates and the percentage of tourmaline falls to about 1/5th of its usual value. Assuming, as Krynine and Mackie suggest, that the blue variety is all derived from pegmatites and that pegmatites contain about equal amounts of brown and blue varieties, one may tentatively suggest that about 25-30% of the tourmaline is derived from pegmatites, less than 20% from pelitic schists and gneisses, and the remaining 50-60% from foliated granites and quartzose metamorphics. Most of the tourmaline of the garnetiferous concentrates is derived from pelitic schists. Slates or phyllites make some contribution to the tourmaline in the extreme west of the Central Basin.

Rutile

Rutile is virtually absent from all Highland granites though a little may form during the weathering of these granites since it is present in some of the granite boulders. The dark-brown variety is probably derived from the Older granites in which it may abound (Mackie, 1932 p. 31). The yellow and red varieties are common accessories in many of the metamorphic rocks, especially the phyllites, gneisses, and granulites, and so it seems probable that most of the rutile is derived from a metamorphic source.

Garnet

The colourless and red-brown varieties are identical with the types commonly found in pelitic schists.

The information which can be derived from the less abundant mineral constituents may be summarized thus:-

Monazite

This mineral occurs in the more acid of the Highland granites and is considered to be indicative of granitic derivation even though it has also been rarely recorded from the Moine schists.

Fluorite

Not a common Highland mineral, fluorite is abundant only in the Kincardine granites, and the Peterhead granite, and is also present in varying amounts in the foliated granites of Glen Tilt and the Central Crampian granites.

Topaz

This is very widely distributed in Scottish granites.

Brookite

The few detrital grains of brookite may have been derived from granite or less probably from schists.

Staurolite, **Chloritoid** and **Glaucophane**

All are indicative of derivation from an area of crystalline schists. The association of chloritoid and glaucophane is particularly interesting, since they have been recorded together only in the Ben Ledi schists

(Mackie in Boswell 1927, p. 139). Indeed glaucophane is not recorded in any other Highland schist.

Spinel

According to Barrow (1912), the green spinel, Ceylonite, is found only in those schists within the sillimanite aureole. It is rarely a product of contact metamorphism and is also occasionally present in the Loch Tay Limestone.

Clinozoisite

Is another mineral characteristic of crystalline schists; it has also been recorded from the pelitic Moine gneiss.

Amphibole

Actinolite and green hornblende suggest derivation from hornblende schists rather than from igneous rocks. Such schists occur at several horizons in the Dalradian succession but the greatest development is in the Green Beds underlying the Ben Ledi Grits at the top of the succession. The amphiboles replace epidote, the mineral which typifies the Green Beds where the grade of metamorphism is very low.

Apatite

The occurrence of this mineral is too widespread to allow any conclusions to be drawn from its presence but its common association with garnet suggests that it is of metamorphic origin. It is a common accessory in the Moine gneisses and granulites and some of the Dalradian mica-schists.

The occasional presence of sphalerite shows that there are a few metalliferous veins in the source area. Little can be deduced from the corundum, sphene, and epidote save that the westerly increase in epidote and the large almost colourless grains to be found in the Glasgow area indicate a westerly increase in epidote in the source rocks.

b) Distribution and Possible Horizon of Source Rocks.

Seven heavy mineral associations have been shown to exist in the Millstone Grit of the Central and Midlothian Basins. It therefore follows that 7 different kinds of source area were being eroded. The character of each may be deduced from its mineral assemblage; their relative positions may be approximately determined from their location in one or other of the basins and from the associated current-bedding directions.

The G-rutile assemblage is derived from the north-west, the C-zircon from the north and the K-rutile from the north-east. The F-zircon of the Midlothian Basin must presumably be derived from even further east or north of the K-rutile while the M-garnet has probably the most easterly derivation of all the associations.

From the nature of the quartz grains it is apparent that all of these assemblages are derived from areas in which metamorphic rocks predominate. The G-rutile and M-garnet sources must be almost entirely metamorphic since 80% of the quartz of these associations is of metamorphic origin. It has been pointed out that the quartz is probably derived from quartzites and from schistose grits similar to the Ben Ledi Grits. If these upper horizons of the Dalradian succession constitute the major source then the changes in these beds traced from west to east should be reflected in the changes from assemblage to assemblage.

The most westerly G-rutile assemblage is very rich in zircon and in rutile. From the elongation of the zircon it appears that this mineral was derived from both igneous and metamorphic, possibly quartzitic sources. A suitable source for the metamorphically derived rutile are the 'Green-Beds' and phyllites of the Cowal-Aberfoyle region which contain more abundant small needles of rutile than any other described Dalradian horizon. These same beds contain a considerable amount of pale green epidote, another of the characteristic minerals of the G-rutile assemblage. The Green Beds differ from almost all other psammitic members of the Dalradian succession in that the tourmaline they contain is a strongly pleochroic brown variety rather than the normal green, pink or honey colour: over 80%, the tourmaline of the G-rutile assemblage is strongly pleochroic in brown. A few grains carry carbonaceous inclusions indicative of a phyllitic derivation.

Adjacent to the Green Beds are numerous coarse schistose grits, such as the Bull Rock, which contain quartz of a type indistinguishable from the metamorphic quartz of the G-rutile association. It therefore seems possible that this assemblage could have been derived from the Upper Dalradian horizons of the south-west Highlands. The nature of the quartz indicates that the grade of metamorphism was low. Epidote is also characteristic of such grades (Phillips 1930) and is replaced at higher grades by garnet and hornblende. That some higher grade metamorphics were also exposed is revealed by the presence of garnet and staurolite.

The schistose grits, Green Beds and phyllites now occupy only a narrow zone along the Highland Border. Elsewhere they are infolded among medium and high grade mica-schists. Formerly however, they must have been more extensive. High grade schists would be exposed only in eroded anticlines and overfolds. If the general structure of the area was similar to that envisaged by Peach or by Bailey then the source being eroded would be to the north of the present outcrop of the beds.

These metamorphic rocks were intruded by one or more granitic masses. The occurrence of monazite and zoned zircons would seem to indicate that some of the granite was of a very acid nature yet Mackie's analyses (1932, p. 38) reveal no monazite in any of the main West of Scotland masses. If, as seems probable, one or more of these masses was being eroded then either Mackie sampled the more basic parts of each, which is unlikely, or else at a higher level the granite masses were more acid.

The C-zircon, K-rutile, and F-zircon assemblages are very similar and are presumably derived from similar, probably adjacent source areas. Almost 70% of the quartz of these associations is of a type found in quartzites, low-grade schists and possibly pegmatites; the remainder is unstrained igneous type quartz. As the principal heavy minerals of each assemblage are those associated with an acid igneous source, few stable species could have been present in the metamorphic source rocks. The reduction in the percentage of epidote in these assemblages compared with the amount in the G-rutile assemblage may reflect a slight north-eastwards increase in metamorphic grade similar to that which Phillips (1930) describes as occurring in the 'Green Beds'. A few shreds of the actinolite or green hornblende which should replace the epidote have been observed in the C-zircon and K-rutile associations. The occasional presence of spinel in the absence of any other metamorphic mineral save a little garnet may indicate that metamorphic limestones of the Loch Tay Limestone type were being eroded. The source of all 3 assemblages included several granite masses which supplied the abundant zircon over 80% of which is igneous the remainder being of quartzitic or schistose derivation. The acidity of these granites apparently increased eastwards since monazite and fluorite are almost absent from the C-zircon assemblage but common in the F-zircon assemblage. Of the granite masses of the Grampian Highlands the more easterly, in Aberdeenshire and Kincardine, almost invariably contain monazite and fluorite (Mackie, 1932): both minerals are often missing from the more westerly masses. It is therefore possible that these same granites were the source of the zircons of the Millstone Grit. Within the source of the K-rutile association there are, as indicated by the very elongate zircons, numerous pegmatites or foliated granites. The latter were probably more important since they could also supply the dark brown rutile which characterises this assemblage. Moreover the K-rutile assemblage contains less blue pegmatitic tourmaline than either the C- or F-zircon assemblages. Most blue tourmaline is present in the former so that more pegmatite veins were present in the C-zircon source than were to be found either further east or further west. The foliated granites of the K-rutile assemblage may be represented by the numerous veins and small masses of 'Older' Caledonian Granites which occur along the south-eastern margin of the Grampian Highlands.

It seems possible that these 4 associations were derived from an area of low-grade schists and quartzites coincident with the present Dalradian area. These rocks were the upper beds of the Dalradian succession which now remain only along the Highland Boundary. The grade of metamorphism increased north-eastwards. The metamorphic rocks were intruded by granites, which were most acid in the extreme east and west, i.e. the 'Newer' Caledonian granites, pegmatites, and in one area by foliated 'Older' granites.

The M-garnet assemblage suggests derivation from an area of garnet and staurolite schists lying somewhere to the east or north-east. Mineralogically this assemblage is indistinguishable from the J-garnet association of the western margin of the Midlothian Basin. These two cannot however have the same immediate source since they are separated by an area occupied by the F-zircon assemblage and since the current-bedding indicates a north-westerly derivation for the J-garnet assemblage. It is therefore probable that both of these assemblages are second cycle sands resulting from the erosion of Lower Carboniferous sediments on the eastern and western margins of the Midlothian Basin. These sediments and the underlying Old Red Sandstone rocks both contain a suitable metamorphic suite of heavy minerals. The very low zircon shape index is another indication of the possible second-cycle nature of the sands. The ultimate metamorphic source probably did lie somewhere to the north-east since south-westerly and westerly foreset slopes are common in the garnetiferous sediments of Lower Carboniferous age.

It has already been suggested that the L-tourmaline and H-garnet associations represent locally derived sedimentary material mixed with the C-zircon assemblage. Along the south and south-west of the Central Basin the top beds of the Upper Limestone Group are missing. Since they were therefore almost certainly being eroded during the Millstone Grit period they would appear to be the most likely source.

Two Upper Limestone Group sands from immediately south of Levenseat did contain those minerals present in the L-tourmaline assemblage and missing from the C-zircon assemblage (Appen. IV). These rocks were therefore almost certainly the source of that part of the L-tourmaline assemblage which was not derived from the C-zircon. It is apparent that the Upper Limestone Group sands which were sampled were not particularly rich in tourmaline so that much of the concentration of this mineral must result from selective current sorting.

Garnet was found to be an important constituent of the sands above the Gair Limestone (Appen.IV) a little to the north-east of the present occurrence of the H-garnet association. Reworking of these beds in a shallow environment of restricted circulation could well have produced the H-garnet assemblage. There was generally only slight contamination by the C-zircon assemblage since the waters carrying it flowed southwards through the area in certain deeper well-defined channels.

The few very garnetiferous sands of the Central Basin have an assemblage almost identical with the M-garnet and J-garnet assemblages and are presumably also derived from erosion of Upper Limestone Group sediments. This is the more probable since they invariably occur close above the Castlecary Limestone i.e. immediately following the pre-Millstone Grit uplift.

Since several of the minor associations are apparently derived from Lower Carboniferous sediments the possibility that the main assemblages of northerly derivation were also second-cycle sands was also investigated. The only obvious source rocks in this direction are the Old Red Sandstone sediments.

From the 5 samples which were examined at various points from east to west between Loch Lomond and Stonehaven it is apparent that these sediments, rich in garnet, apatite, and iron ores (Appen.IV) could not in fact have supplied the material of the C-zircon, F-zircon, K-rutile and G-rutile assemblages all of which are probably derived directly from igneous and metamorphic source rocks.

CHEMISTRY OF THE DEPOSITIONAL ENVIRONMENT

The chemistry of the environment in which any sedimentary formation was deposited may be in part deduced from the faunal content of the sediments and from the nature of the authigenic minerals and cement.

Unfortunately, the Millstone Grit sandstones are, as a whole, almost devoid of fossils. Within the marine bands much of the fauna e.g. the brachiopods indicates a saline environment: toward the top of the marine bands and in particular in Nos. 5 and 6 Marine Band Groups the characteristic fossils are lamellibranchs adapted to life in brackish to fresh water conditions. It is therefore obvious that considerable fluctuations in salinity occurred during the deposition of the Millstone Grit sandstones. Since the most prolific lamellibranch fauna is to be found in the northern part of the Central Basin it would appear that there was a southwards increase in salinity. Also since the Upper two 'marine bands' contain few of the truly marine forms of the lower marine bands it was seen that the salinity was lower during deposition of the Upper Millstone Grit sandstones than it had been during the deposition of the lower members of the Series. The occasional goniatites found below the No. 3 Marine Band Group also indicate a saline environment: their absence above this horizon may well result from freshening of the water over the area of deposition.

In all of the concentrates the mean size of the opaque minerals, iron oxides with a very little pyrite, is considerably greater than that of any of the heavy detrital species with which they are associated.

Since they have a greater density than any of these minerals the opaque minerals are not the hydraulic equivalents of the non-opaque detritals and must therefore be largely authigenic in origin. As beds rich in opaque minerals occur in association with less 'iron-rich' sands it seems probable that the authigenic minerals formed during or immediately after deposition. The only other authigenic constituents of any importance are the titanium minerals anatase and brookite of which the former is by far the most common.

Of the chemically precipitated cementing agents the carbonates and haemetite are probably both primary precipitates. Where either is abundant the quartz grains may appear to be 'floating' in the cement (Pl.9). Such a condition would be unlikely if the cement were formed after the grains had been packed together. Much of the carbonate is dolomite or ankerite ($Ca,(Mg, Fe)(CO_3)_2$) rather than calcite.

The interrelation between the amounts of iron oxides, anatase, and carbonate cement as observed in Bogside No. 4 bore are shown in fig. (66). The important features of the distribution may be enumerated thus:-

1) Distinct maxima in the iron oxide percentage occur within the upper Marine Band Groups.
2) Carbonate maxima are related to the lower marine bands.
3) A carbonate cement is ever present below No. 3 Marine Band but is often missing from the upper part of the Series.
4) Carbonate and iron oxides are in antipathetic relationship. High values of both occur together however within Nos. 1 and 5

Marine Band Groups though in the latter the maxima are not coincident.

5) Anatase is always present where there is carbonate cement but only occurs once in the absence of such a cement.

6) There is a tendency for the highest percentages of anatase to accompany iron oxide maxima. This is subordinate to 5

From elsewhere in the Central Basin it is found that high percentages of anatase and brookite occur only in the presence of abundant iron oxides.

Iron carried in solution by streams largely as $Fe\ Cl_3$ or $Fe\ F_3$, tends to be precipatated as a result of the electrolytic action of sea water (Moore and Maynard 1929). Girdles of iron rich sands are therefore commonly found ahead of actively prograding delta fronts where much dissolved iron is being carried in and where there is a change from fresh to brackish and salt conditions (Van Andel and Postma 1954, p. 157). Deposition also occurs in shallow poorly aerated waters in the presence of abundant organic debris.

The initial precipitate is commonly of ferric hydroxide whose solubility is very low under the alkaline conditions which prevail in sea water. It is therefore precipitated before the concentration can become very high so that the resultant percentage of iron oxides or limonite in these sands is low. If however, the bottom waters are acid as they would be where they were little agitated and where there is abundant decaying organic matter then much higher concentration of

$Fe(OH)_3$ is possible. Precipitation by reduction to FeS_2 and Fe S: n H_2O or as $Fe(OH)_3$ where the pH increases will result in much higher percentages of iron salts. The very high concentrations of iron in the marine bands result from the higher percentage of organic matter present at these times. Diagenetic decay of this organic matter resulting in the evolution of H_2S and CO_2 will produce acid reducing conditions in which the iron salts of the organic matter will be converted to sulphides, thus further increasing the amount of authigenic iron minerals in the sediment.

The presence of a primary calcite cement implies that the waters of the depositional basin were saturated with $CaCO_3$. Such an aqueous solution is alkaline. In such an environment concentration of $Fe(OH)_3$ is not possible and thus there is the observed antipathetic relationship between carbonates and iron oxides. Moreover, decay of organic matter in the presence of calcium carbonate solution does not readily result in the acid reducing conditions which favour the formation of iron sulphides since the CO_2 evolved reacts with the calcium carbonate to produce bicarbonate.

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca(HCO_3)_2$$

The limy facies of all of the Millstone Grit marine bands are, with the possible exception of No. 2, chemical precipitates. Strongly alkaline conditions prevailed throughout the Central and Midlothian Basins while such beds were being deposited.

It has been suggested (P. 98) that the marine bands represent periods of silting up and stagnation, the limy shales and thin dolomites being analogous to salt pan deposits. At the same time however, considerable plant growth was taking place in swamps and marshes. The remains of this vegetation form the thin coals so closely associated with the marine horizons. In these more swampy areas the environment would be acid. Considerable lateral and vertical fluctuations in pH existed during deposition of a marine band group. Waters rich in iron salts and organic material flowing into a more alkaline environment would precipitate most of those iron salts to produce sediments rich in iron. Where the percentage of calcium carbonate was insufficient to neutralise the organic acids only iron would be precipitated: where evaporation and $CaCO_3$ content were greater then both iron and carbonates are precipitated, the percentage of iron found in the sediment being lower because of the inhibition of diagenetic sulphide formation.

From fig. (66) it would appear that in the northern part of the Central Basin, and possibly throughout the greater part of that basin, deposition of the Lower Millstone Grit sediments took place in a shallow marine environment in which the pH was commonly in excess of 8 - such is the pH of waters rich in carbonates. The absence of carbonates from the upper part of the Series indicates deposition in an environment which was neutral or slightly acid except during deposition of the marine bands when the pH was very variable.

The anatase of the Millstone Grit sediments is almost wholly derived from ilmenite which explains why high percentages of anatase are commonly associated with sediments rich in iron ores. The relation between anatase and carbonate may be explained by the fact that iron oxides including ilmenite, while stable against weathering, are partly converted to ferrous carbonate and ferric hydroxide by the action of carbon dioxide and water i.e. in the presence of $H^{++}CO_3''$

$$\underset{}{FeTiO_3} + H_2CO_3 \rightleftharpoons FeCO_3 + H_2O + \underset{\text{anatase}}{TiO_2}$$

The necessary H_2CO_3 may be produced by the transformation of bicarbonate to carbonate, the probable mechanism where anatase is associated with precipitated carbonates, or by the decay of organic matter. The latter is probably the more common and very high percentages of anatase may be found in sands where iron sulphides are forming as a result of organic decay. The relation between the two in the Gulf of Paria is shown in fig. (67). Anatase appears to be the only titanium oxide forming under very acid conditions. Both anatase and brookite may form where the environment is neutral or alkaline: abundant formation of anatase only takes place where reducing conditions exist in the recently deposited sediments; brookite may form where the environment is oxidising.

Formation of a primary haematite cement is most common under very shallow water conditions with sufficient oxygen in the agitated waters to produce first $Fe(OH)_3$ and then Fe_2O_3. Precipitation is aided by an alkaline environment and may not occur in the presence of organic acids (Vogel, 1945, p. 185).

It is therefore tentatively suggested that the pH and redox potential of the upper layers of sediment, though not necessarily of the depositing medium, may be estimated from the authigenic minerals and cement as follows:-

1) Haematite cement - oxidising and probably alkaline
2) Anatase and Calcite - alkaline, possibly reducing
3) Anatase and Limonite - acid and reducing
4) Anatase, Brookite, and Limonite - neutral and weakly reducing
5) Brookite - neutral or alkaline, possibly oxidising

Greensmith (1957) suggests that the presence of silica cements, kaolinite and hydrobiotite indicate an acid environment of deposition for sands of a type almost identical with those of the Scottish Millstone Grit. Wager (1940) pointed out that hydrobiotite was formed in an acid environment. The use of silica or kaolinite is questionable. Van Andel and Postma (1954) found no correlation between pH and the amount of kaolinite. Since secondary growth of SiO_2 is found in sands with a calcite cement which would be deposited in an alkaline environment, Greensmith suggests that secondary growth of silica occurred during transport in acid waters before the alkaline environment was reached. Apart from the time involved in formation of a secondary rim two features of the Millstone Grit sands suggest that this mechanism is not generally applicable. The secondary rims of adjacent grains interlock or else the boundary becomes straight; these grains would only be together after deposition. Moreover growth of the rim is inhibited where the clay cement impinges on the grain. Secondary silica would be deposited in an acid environment but may have formed long after deposition and burial of the sandstone. The development of euhedral quartz is enhanced by a calcite cement because of the increased solubility of SiO_2 in an alkaline environment. The relation between the two is given by Correns (1951)

$$Ca\,CO_3 + H_2SiO_3 + H_2\,CO_3 \rightleftharpoons Ca^{++} + 2H\,CO_3' + H_2O + SiO_2$$

SiO_2 is deposited if the environment is acid, $Ca\,CO_3$ if it is alkaline.

The pH will increase rapidly away from the margin of each quartz crystal, and will tend to be greater at projecting points of the grain than in embayments. Solution will therefore be greatest at projecting points: deposition may or may not occur in embayments but is likely to occur where several quartz grains lie side by side since at such points the pH will be relatively low. Solution and deposition will produce straight crystal faces.

The percentile ratio of iron oxides to non-opaque detritals is indicated in fig. (68): the percentage of anatase and brookite in the same Lower Millstone Grit sandstones are contained in figs. (69) and (70). It is apparent that distribution in each of these species is related to the distribution of the various sedimentary provinces.

Over that part of the Central Basin occupied by the C-zircon assemblage most of the iron ores, ilmenite and magnetite, are of detrital origin; the percentage is commonly a little under 50. Between 1 and 2% of anatase and little or no brookite are present. The cement is of clay minerals in which there is variable development of mica and chlorite. Sericite and muscovite form rather than biotite presumably because of the scarcity of iron. Only a very little limonite is ever present except in the few garnetiferous sands where it is patchily developed. The environment of the upper layers of sediment was therefore reducing and weakly acid. Little organic material was present to produce iron compounds except in the garnetiferous sands derived by local erosion of exposed Upper Limestone Group sediments. In the well-sorted 'beach' sands on the eastern side of the basin anatase is virtually absent, being replaced by as much as 3% of brookite which would indicate a neutral to alkaline, oxidising environment such as would be found on a marine beach. Over most of the Central Basin the waters were saline and slightly alkaline.

In the K-rutile assemblage of Eastern Clackmannan there is an occasional development of high iron percentages. The cement is now of calcite and clay. About 2% of anatase is present. The environment is therefore alkaline and reducing. The high iron concentrations are caused by precipitation due to increased salinity. Since calcite is not found in any of the C-zircon sands, the K-rutile carbonates may have been carried in in solution and precipitated where the pH is increased.

A very well marked girdle of iron-rich sands is developed in the G-rutile delta front; the percentage of iron oxides and limonite is commonly over 200. Anatase is abundant, brookite present though usually in lesser amounts. Sericite and biotite are commonly developed with the clay matrix. These factors suggest a rapid increase in salinity ahead of the G-rutile delta complex with the precipitation of $Fe(OH)_3$. The reducing conditions within the sediment are probably due to organic decay. Acid conditions were not common but the rapid fluctuation in the anatase/brookite ratio suggests rapid changes in pH probably due to mixing with the alkaline waters of the central part of the basin.

The dependence of chemical environment on sedimentary province is well seen in the Torwood succession. Almost all of these sands carry a C-zircon assemblage and have the typical low iron-ore, low anatase values of that province. About No. 2 Marine Band however, mixed C-zircon and G-rutile sands appear. In these sands the percentage of iron is increased fivefold and over 8% of brookite appear. This mineral is absent from the remainder of the succession.

Development of authigenic minerals in the L-tourmaline province is similar to that in the G-rutile province. Here too there was a change from fresh to saline water, and burial of plant material whose decay induced strongly reducing conditions. Plant fragments and logs are commonly observed at Levenseat.

That the environment was different in the Midlothian-Fife Basin is apparent from the virtual absence of anatase and complete absence of brookite, one or other of which is always present in the Central Basin. Common cements are haemetite and limonite so that the sands have a red colouration never found in the Central Basin. Calcareous cements are occasionally present in the M-garnet sands. In the waters of the basin and the sediments deposited therein, strongly oxidising conditions existed. The organic content was lower than in the Central Basin being insufficient to produce reducing conditions. Over most of the Basin pH was fairly high (around 7). In the extreme south of the

Midlothian Basin however, where considerable percentages of anatase suddenly appear there was probably a sufficient increase in organic debris to produce acid reducing conditions.

In the Upper Millstone Grit sands the percentage of iron (fig. 71) has increased to about 75 over that part of the Central Basin occupied by the C-zircon and K-rutile assemblages probably as a result of a decrease in pH with consequent concentration of $Fe(OH)_3$. The K-rutile delta front is now an area of iron-rich sands. With the westwards diversion of G-rutile distributaries the girdle of limonitic sands has disappeared from the western part of the basin. Submergence of the low positive area south of Levenseat has led to the disappearance of high iron percentages in the south-east of the basin.

Development of anatase (fig. 72) is less abundant than formerly and many sands in the northern part of the basin contain no anatase at all. There is a considerable development of anatase and brookite (fig. 73) in the southern part of the basin. A few sandstones in the northern half of the basin now have a little haematite cement. Further south the cement is of clay and limonite. Authigenic biotite is formed in most of the sandstones. The environment was much more uniform than previously. Slightly acid conditions now prevailed over most of the basin: the southerly increase in brookite indicates slight southwards increase in pH so that neutral conditions probably prevailed in the Newmains district. The redox potential also decreased slightly further south. Lack of anatase in the north of the basin and haematite cements indicate oxidising conditions. Slightly reducing conditions existed at other times in the north of the basin and were persistent further south.

The area of the H-garnet assemblage is quite distinctly different from the Central Basin. Here the percentage of iron ores is always very high; anatase is abundant, brookite absent. Much secondary biotite has formed. It is apparent that over this area conditions were acid and strongly reducing, probably as a result of a considerable increase in plant material of local derivation.

In the Midlothian - Fife Basin a little anatase is now present in all of the Fife concentrates but absent from Midlothian save in the extreme south and in the area of the J-garnet assemblage. Haematite cements are still common in Midlothian. The formation of anatase rather than brookite suggests that the environment is slightly acid. Reducing conditions exist in Fife, at Joppa, and in the extreme south: oxidising conditions are found throughout the remainder of the Midlothian Basin.

The chemical environment of the Lower and Upper Millstone Grit sands is indicated in figs. (74) and (75).

DEPOSITIONAL HISTORY OF THE MILLSTONE GRIT

During deposition of the sediments of the Upper Limestone Group much of the Midland Valley has been submerged. Immediately prior to the formation of the Castlecary Limestone however, the whole area was subject to a series of uplifts as a result of which the depositional area was restricted with the emergence of an 'island' over Northern Ayrshire and along the southern margin of the Central Basin. Emergence also took place in East Lothian and East Fife, in north-west Stirlingshire and along part at least of the anticlinal arch which separates the Central and Midlothian Basins. There was thus a re-establishment of the two district basins of sedimentation which Goodlet (1957) had shown to exist during deposition of the Lower Limestone Group (fig. 76). The general level of the area was somewhat higher than it had been at that time so that the positive areas were now more extensive. There is an obvious relationship between the location of the margins of the basins and the occurrence of the Lower Carboniferous lavas. Wherever they are approached fluviatile or beach type sands appear. While the lavas now appear to control the extent of the basins it may well be that the location of the original lava eruptions was influenced by the position of the down warping at the edge of the very early Carboniferous or even pre-Carboniferous basins.

The Castlecary Limestone is largely a chemical precipitate formed by evaporation of the saline waters of these basins. It seems probable that the former drainage system would be considerably disrupted by the uplifts and the limestone may have formed before the new drainage system was properly established. It is frequently floored by a nodular seam of barytes which was presumably precipitated before the dolomite because of its smaller solubility. The degree of fine clastic material increases upwards in the limestone and a sparse brackish water fauna appears. These changes reflect the gradual establishment of the new drainage system with consequent increase in the volume of water entering the basin. Eventually precipitation ceased and the rivers carried in a mixture of fine clastic material and plant material derived from the flora which had become established on the newly-exposed areas. Clastics and plant debris together produced the bituminous shale which frequently overlies the Castlecary Limestone especially towards the margins of the basins. The Castlecary Limestone is missing at several localities within the Central Basin and this has formerly been ascribed to pene-contemporaneous erosion although there is no evidence of scouring of the underlying sediments. As it is here considered to be chemically precipitated its absence is ascribed to local decrease in the concentration of calcium and magnesium carbonates most of which was due to influx of fresh river water. It was therefore only patchily developed towards the edges of the basin at such places as Levenseat. It is also missing over an area extending west-south westwards from eastern Clackmannan (Francis, 1956). This area coincides exactly with the K-rutile association. It would appear that the river carrying the K-rutile association was established very early and that the volume of water discharged was sufficient to affect the concentration of carbonates ahead of its advancing delta and so prevent precipitation.

As the main drainage systems become established material of sand grade was swept into the basin. Initially these sands contained considerable amounts of garnet indicating that considerable erosion of the newly-exposed Upper Limestone Group sediments was taking place. The amount of such erosion decreased rapidly. It persisted however for some time along the southern margin of the Central Basin and along the eastern edge of the Midlothian Basin to produce the L-tourmaline and M-garnet associations of these areas. Almost all of the detritus being swept into the basins was derived from a metamorphic area lying at no great distance to the north. The rocks being eroded were mainly quartzites and schistose grits together with slates and phyllites which were common only in the west. The rocks were of low metamorphic grade and are considered to have belonged to the Upper Dalradian horizons above the Loch Tay Limestone. These metamorphic rocks were intruded by both 'Older' and 'Younger' granites and by pegmatites.

Three distinct river systems were discharging into the Central Basin. The most westerly of these discharged a few miles north of Glasgow through several distributaries: another entered the basin north of Stirling: the third built its delta in eastern Clackmannan. There is evidence of only one river system flowing into the northern end of the Midlothian-Fife Basin. By virtue of the variations in the character of the rocks included in the regimen of each of these river systems, the sands discharged from each carried a somewhat different assemblage of heavy minerals which have been described in Chapter (VII) as the G-rutile, C-zircon, K-rutile, and F-zircon assemblages.

In consequence of the several rivers discharging at various points around the northern perimeter of the Central Basin, the current direction within the basin was very variable. Ahead of the growing delta in Clackmannan the prevailing currents were westerly: ahead of the north-westerly inflow the current direction was in the south-east quadrant. Elsewhere it was southerly with slight clockwise rotation in the south-east of the basin as it was deflected by the southern bar and by rivers flowing from that area. Superimposed on the other current directions was a marked westerly flow towards the south-westerly outlets from the basin.

In order to escape in this direction the waters of the Central Basin had to breach the continuous arc of Lower Carboniferous lavas which encompasses the western part of the basin. While it is not possible to be absolutely certain of the point of egress it seems very probable that they coincided with one or both of the narrow 'grabens' which traverse the lavas at Barrhead and Johnstone. The former coincides with the Dusk Water fault. The currents flowed directly towards these downfaulted blocks and there is a tongue of thicker sediments also directed towards them. The presence of a similar tongue in the Lower Limestone Group sediments suggests that the same channels were operative at that time. From these channels the water flowed through the northern margin of the Millstone Grit lavas of North Ayrshire into the very shallow, sometimes partly lava-filled Kilmarnock Basin, separated by a lava plateau from South Ayrshire Basin. The Kilmarnock and South Ayrshire Basins may have been continuous around the western margins of this plateau.

Over the greater part of the Midlothian-Fife Basin the currents flowed southwards away from the mouths of the river system discharging into the northern end of the basin. Only along the eastern margin where the short swift streams draining the exposed Lower Carboniferous sediments entered, did the currents veer westwards. This basin too was almost completely land-locked and lacustrine in character. The outflow from the southern end of the basin may have passed southwards through the Southern Uplands but was more probably diverted south - westwards to enter the Central Basin, east of Levenseat or else the Douglas Basin, an easterly extension of the Ayrshire Basin.

Since the Lower Millstone Grit sediments of the Central and Mid-lothian Basins are considered to have been deposited in a lacustrine rather than a shallow open marine environment they were not laterally continuous with the Millstone Grit deposits of the North of England. The fauna which evolved within them would therefore have differed specifically from the North of England fauna. The considerable differences which do in fact exist have been summarised by Macgregor (1930, pp. 458-485). Most important is the unusual lamellibranch fauna of the Scottish Millstone Grit. Of the many species, Dr. Wheelton Hind (1908, p. 332) considered 50% to be unknown elsewhere in Europe. The stock from which these species were derived was trapped in the two basins by the pre-Millstone Grit uplifts. In both basins the salinity was sufficient at this time to support a marine fauna - e.g. possible salt pseudomorphs have been recorded in the Castlecary Limestone - but fluctuated considerably. It would always have been greater in the centre of the basins than towards the points of influx of the rivers. Only those species which could withstand the salinity changes or could migrate to a part of the basin where the salinity was suitable could survive. These were not the same species which developed in the shallow marine environment of the North of England. The extreme paucity of the goniatite fauna of Scotland is probably to be attributed to the same cause. Boring has revealed that the shales which make up the Lower Millstone Grit of the deepest, consistently saline, never silted-up south-west of the Central Basin are crowded with lamellibranchs, brachiopods, crinoids and fish scales.

Considerable lateral facies variation existed in both basins at this time with fairly coarse sands and gravels close to margins of the basins giving way inwards and southwards to fine sandstones and shales. The grain size distribution of the sands is very variable. In the Clackmannan area of the Central Basin fluviatile and delta-front F and M types were being deposited. Elsewhere the sands were of the MC type found in shallow marine and lacustrine environments, except at Linlithgow where very well-sorted sands were deposited on the eastern beaches of the basin. The influx of ill sorted material from south of the Central Basin produced the fringe of 'dumped' B and F types found at Levenseat. The appearance of fluviatile sands associated with the north-westerly influx occurred rather later.

In the Midlothian Basin the better sorted delta-front M sands which are most common indicate that this basin was shallower or less restricted than the Central Basin. Along the eastern edge of the basin B types were formed as a result of the deposition of locally derived material.

The difference in depth and reworking in the two basins is also indicated by the contrasting development of authigenic minerals. In the deeper Central Basin where little reworking was taking place the decay of organic debris resulted in an acid reducing environment under the top layer of sediment. In Midlothian the lower organic content and comparatively well oxygenated shallow waters prevented the onset of reducing conditions and haematite was deposited in place of the anatase and limonite of the Central Basin.

In the Central Basin the rate of subsidence was variable and not in phase with the rate of deposition, except perhaps in parts of the Clackmannan delta front area where the lower part of the succession is dominantly arenaceous. Elsewhere the grain size of the sediments shows marked vertical fluctuations with the interbedding of sandstones, shales, and fireclays. Very occasionally during the deposition of these earliest Millstone Grit sediments when the basins were partly silted, vegetation spread into the depositional areas. Each such advance is now marked by a thin coal. By no means all of the coals now found among the Millstone Grit sediments were formed in situ. Many are parrot coals formed partly from drifted-in logs, partly from the marine organisms inhabiting the basin. These hard sclitty coals which contain a high percentage of very fine clastic debris are most common in the south and west of the basin which were never completely silted up at this time. They probably form contemporaneously with the autochthonous coals of the silted up areas.

On three occasions the concentration of carbonates became so high that precipitation occurred with the formation of the thin dolomitic limestones or limy shales of Nos. 0, 1 and 2 Marine Bands. These marine horizons are often missing, as was the Castlecary Limestone, close by the mouths of the rivers discharging into the basin because there the concentration of salts was greatly reduced. Concentration was favoured by shallow waters and by a reduction in the volume of water entering the basin. Most suitable conditions were therefore attained when plant growth was most abundant and so these limy horizons are often closely associated with thin coals. The increased salinity of the waters from which the carbonates were being precipitated permitted the extension of the generally localised marine fauna over the greater part of the basin.

Since all of the Lower Millstone Grit deposits are of shallow water origin the rate of subsidence must have varied in different parts of the basin as the interval between the Castlecary Limestone and the No. 2 Marine Band is commonly in excess of 150 feet in Clackmannan, yet only some 60 ft. surther south and little more than 20 feet in the south-west. The greater load deposited in the northern part of the basin is considered to have produced this faster subsidence. This same area continued to sink most rapidly through the whole of the

Millstone Grit period.

In the Midlothian Basin the rate of subsidence was much more uniformly related to the rate of deposition. Almost the whole of the lower 200 feet or more of the succession is therefore occupied by delta-front sands of the M and FM types. The B types of the eastern margin of the basin rapidly disappeared as the adjacent land was eroded. Three thin marine horizons are patchily developed in this basin also. In Fife they were again limy shales but in Midlothian where only the two upper horizons are present ironstones have been developed rather than limestones. These marine horizons are to be correlated with Nos. 0 to 2 Marine Bands of the Central Basin only if the decreased flow of water which produced both was the result of slight earth movements affecting the whole of the Midland Valley i.e. if the more extensive vegetation was the result of slight uplift.

That some regional control did affect sedimentation in both basins is suggested by the fact that in both basins there now ensued a period of very slow sedimentation. The rivers from the north were nearly at grade, and, in the absence of earth movements, both basins were almost completely silted up. Subsidence within the basins was very slow. Thick fireclays and shales with several thin coals were formed in the Central Basin: in Midlothian where some lime was also being precipitated marls and fireclays were deposited. Within these deposits the limestones or ironstones of No. 3 Marine Band Group were formed. The Midlothian Basin was probably even more shallow and more stable than the Central Basin. Within it several plant beds formed together with coals which locally are very thick. The shallow area persisted longest in Midlothian. In the Central Basin and in Fife rejuvenation and local uplifts led to the formation of coarse delta-front sands with only a temporary return to slower sedimentation during formation of the No. 5 Marine Band Group.

By this time the low positive area around the southern margin of the Central Basin had sunk to such a degree that in the Lanark area it was below sea level. This resulted in a marked change in the current circulation of the basin. From the northerly C-zircon source, which was now by far the most important of all sources, the rivers flowed south into the basin. From their mouth the currents continued southwards through the basin passing into the Ayrshire Basin via several channels in this Lanark Gap. The presence of some westerly currents in the Glasgow area indicates the continued presence of a second outlet through the Barrhead and Johnstone channels. A southerly current still flowed through the Midlothian Basin.

The final phase in the sedimentation of the Millstone Grit was prefaced by further rejuvenation. Sands and gravels swept into both basins to be deposited ahead of the rapidly growing deltas. Subsidence proceeded fairly evenly in both basins so that little vertical facies variation is to be found except at an early stage of this phase when a 6th marine band was developed in parts of the Central Basin. Thin coals are also developed where subsidence was momentarily out by the rapid deposition, but are of little or no account, lost among the 600 feet or more of massive sandstones which cap the succession where it reaches its fullest development. Almost all of the Midlothian Basin was occupied by delta-front M sands. Conditions were much more mobile in the Central Basin with the shoreline now advancing southwards into the heart of the basin, now retreating even more rapidly as subsidence accelerated. In consequence, the southern half of the basin was occupied by delta-front sands, the northern half by a combination of the same M types with FM and fluviatile F types.

As a result of the greatly increased volume of water entering the basins the salinity was low. Very few of the marine species of the Lower Millstone Grit are ever found among these top sandstones. In the shallow parts of both basins the environment was oxidising as neutral or slightly acid. Weakly reducing conditions existed in the deeper southern parts of the Central Basin and in Fife.

At last, erosion of the very low-grade metamorphic source of the Millstone Grit sands had proceeded to such an extent that the volume of sediment being supplied to the basin from these rock types decreased. The Carboniferous Limestone Series had been derived from a metamorphic source of somewhat higher grade but, following the pre Millstone Grit uplifts this source had ceased to supply any significant amount of detritus. Now however, as the Millstone Grit source was eroded, the same rock types which had supplied the Carboniferous Limestone sands became, once again, the most important contributors. These new source rocks may have been exposed in the same areas as formerly but they may also have underlain the lower grade metamorphics of the Millstone Grit source. Gradually at first and then with ever increasing rapidity the percentage of garnet increased till it became once more, the principal heavy accessory mineral of the sands. The advent of the garnetiferous sands, interbedded as they are with coal and shale, heralds the arrival of the Coal Measures and marks the completion of the Millstone Grit phase of deposition. Palaeo-geographic reconstructions of the physiography of the Midland Valley at the beginning and towards the close of this phase of deposition are contained in figs. (77) and (78).

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